INDIVIDUAL DIFFERENCES IN COLOUR VISION

R. W. PICKFORD

M.A., Ph.D., D.Litt., Senior Lecturer on Psychology
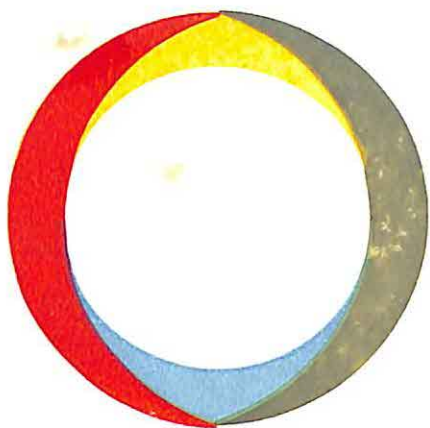
Glasgow University

INDIVIDUAL DIFFERENCES
IN COLOUR VISION

A CAREFUL report of extensive re-
searches which have been carried out
during the last eight years. Eleven
hundred normal subjects and one
hundred and seventy-eight colour-
blind have been tested. The results of
such an extensive series of experi-
ments have not been published before.
It is valuable both for the measure-
ment of individual differences in
normal colour vision (which have
important implications in industry),
and for the measurement of such diff-
erences among the colour-blind. The
various types and their peculiarities
are classified, and the author puts
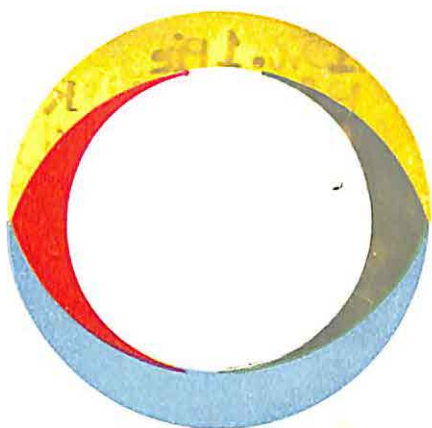forward his theory of four-colour
vision.

With a coloured Frontispiece and
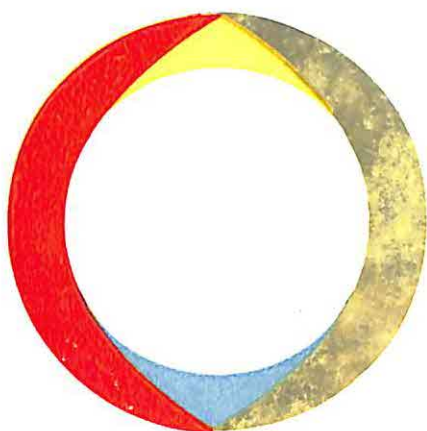*32 illustrations in the text*

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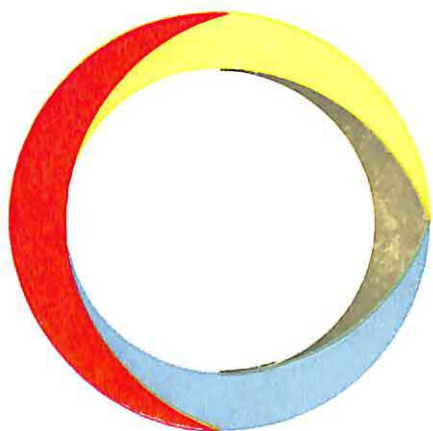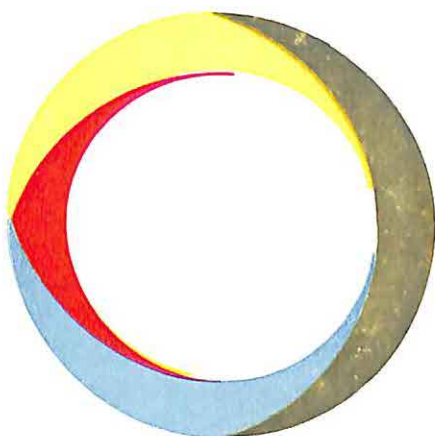
I. Normal   II. Red-Green Blind

III. Yellow-Blue Weak

IV. Green Anomalous   V. Red Anomalous

     Frontispiece

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by

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M.A., Ph.D., D.Litt., Senior Lecturer on Psychology,
Glasgow University

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TO ALEXIS

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DIAGRAMS

FOREWORD

by

PROFESSOR SIR FREDERIC BARTLETT, C.B.E., D.Sc., F.R.S.

IN my judgment this book is of such substance and quality that it can stand well by itself and is in no need of any Foreword. Nevertheless, there are particular reasons, apart from my long-standing friendship with the author, which make my present task to me an uncommonly pleasing one.

As I read the pages of this recorded research I was again and again taken back in memory to the earlier days of the British Psychological Society, when W. H. R. Rivers, C. S. Myers, William McDougall and others discussed, with tremendous and friendly heat, the merits and demerits of the various colour theories. Probably, and for obvious reasons, most investigators in this field who have preserved a pre-dominantly psychological approach have, whatever may have been their ultimate conclusions, felt a considerable amount of sympathy for some form of the explanatory system associated with Hering. Dr. Pickford is no exception; but he has expounded the evidence, in so far as this is concerned with direct colour experiences, probably more clearly and comprehensively than any other writer has done. There are, and probably always will be, great difficulties in making the step from the study, by classification and analysis, of individual differences in perception to any decisive conclusions about the nature and number of the physiological response systems involved. In particular it always seems necessary to make some such assumption as that nature works with the most economical equipment; but maybe it does not. So perhaps differences will always develop between those investigators who approach the phenomena of colour response from the receptor side, and those whose approach is either physical or psychological. However this may be, nobody who reads this book will be able to doubt that Dr. Pickford has carried out a vast amount of well-planned experiment, has expounded his results with clarity and good humour, and has the enviable gift of achieving definiteness without intolerance towards those who may be equally definite but in a different sense.

It would be wrong to suggest that the only, or even the main

merit of this book lies in its contribution to a theory of colour vision. In a practical way also the volume is important. In all modern communities colours are much used as signals for particular types of action, and if those signals are misinterpreted, or only tardily interpreted, in most cases inefficiency and in some cases avoidable disaster may result. Many common views about what is and what is not dangerous in the way of colour perception defects are either confused or incorrect, and some of the commonly accepted tests for such defects are none too reliable. It may be, as Dr. Pickford himself suggests, that his Four-Colour Test (see especially pp. 303–4 and 317) is still susceptible of much improvement, but it does seem that on the evidence assembled it represents an important practical gain.

Further, there is no other book I know in which the general methodology of this type of psycho-physical investigation is dealt with anything like as well. Again and again—but none too often—we read how the colour-defective observer will use indirect and subsidiary cues to help him, sometimes without knowing what he is doing. We are shown to what a large extent the observer may be influenced by the unwary experimenter. In these and other ways the book is a contribution to the methodology of basic psychological experiment which will be found to have very wide applications.

Much more could be said in praise of this book and, no doubt whatever, much more will be said in its criticism. There is, however, one thing about which supporters and opponents are likely to agree, and that is that Dr. Pickford has found out how to write about exceedingly technical matters in a manner which both the expert and the general reader will find deeply interesting. Perhaps this is because, being a good psychologist, he never forgets that the people who respond to his colours do other things as well.

PREFACE

AFTER a century or more of intensive and brilliant research there is still much doubt and controversy about the essential nature of the psycho-physical functions of colour vision and about its variations in the population. The aims of the present research have been three-fold: (1) To make an efficient test of colour vision, which reveals the differences between people with normal sensitivity, which compares them directly even with the most defective, and which distinguishes clearly between the different kinds of defects; (2) To use this test to study variations of colour vision, to discover the types of variation, their frequency and distribution in the population, the way they are inherited and affect the individual in daily life; (3) To throw light upon theoretical problems of colour vision, and to discover which colour vision theory most adequately accords with the facts.

This book gives full details of the apparatus used and of the techniques of testing employed. An account will also be given of the various difficulties which were encountered: (a) in the design and construction of the tests from a purely physical point of view; (b) in dealing with different types and degrees of colour defect and sensitivity, and of the precautions to be taken in separating them efficiently; (c) in dealing with different personal attitudes of the individuals tested, the importance of which cannot be overestimated.

Like intelligence testing, in which the majority of psychologists are now experienced, colour vision testing is a matter for the clinical expert. In testing intelligence it is essential to encourage the subject to do his very best under strictly standardised conditions, but without giving him more credit than his due. In colour vision testing the same principles apply, but it is of vital importance that the tester must be constantly on his guard lest the subject is better at testing him than he is at testing the subject. I am indebted to Dr. R. A. Houstoun for pointing this out to me, and shall explain and justify the observation more fully later, when the special peculiarities of numerous colour-blind individuals will be discussed in detail.

In colour vision testing there is much more risk of under- than of over-estimating any defects the subject may have. Group testing for colour blindness, which gives the individual far too many opportunities of evasion, should be abandoned altogether, and is useless

even as a preliminary to more careful individual testing. One of my most distinguished correspondents on colour vision, who wished to do group testing, explained that most of his subjects were children, and that they at least had not learned to test the tester. I share his benevolence but not his optimism. Children are experts at testing adults, and this is one of the qualities which makes them interesting. Colour blind persons, even children, tend quite unwittingly to exploit every possible kind of advantage which their companions, who do not believe that any person can see the same world and see it in such a different way, unintentionally offer.

The experiments which are described in this book were begun in 1942, as a result of three circumstances. The first of these was my acquaintance with three red-green defective men: Mr. Joseph F. Simpson, Dr. G. H. Haydock, and Mr. John McDonald. Mr. Simpson had discovered, many years before, that he could read the " colour blind " figures in the Ishihara test easily and could guess at the " normal " figures only with very great difficulty. He was aware of no colour vision defect in himself in daily life, except a slight doubt about the naming of certain desaturated greens and a difficulty in finding red golf tees in the green grass. He had kept his difficulty with the Ishihara test strictly to himself, but it was found that he called the Ilford Spectrum-Yellow colour-filter " green ". This led to a careful study of his colour vision with Holmgren's Wools, Stilling's Tables, Ishihara's Test, Edridge-Green's Beads and with a spectrometer. He was a red-green defective of a kind which these tests did not determine unequivocally, namely green anomalous, and his condition will be discussed further in relevant parts of the book.

Dr. Haydock admitted in a conversation that he had a difficulty in finding his golf tee if he was foolish enough to use a red one. He added with firmness that he was not colour blind, but this conversation led me to repeat upon him the tests carried out on Mr. Simpson, and he was an extreme red-green defective. Numerous discussions about the appearance of colours and about the distinctions between them, and carefully directed questions and tests revealed an enormous amount of what might be called " clinical " information concerning colour blindness. Insight was gained into the nature of the difficulties met with by the colour blind, how they overcome those difficulties, and how their habitual and often most ingenious, though often unconscious methods or " tricks " for avoiding detection, may be circumvented in critical tests. Frank discussions with Dr. Haydock were perhaps more illuminating than any book on colour blindness.

From Mr. McDonald, who was another extreme red-green defective, much preliminary information was also collected.

The second circumstance which led to the present research was the conviction that there was need for a test of colour vision defects more efficient than any in ordinary use. This conviction arose partly out of the discussions with these three men, partly as a result of colour vision tests carried out in psychology classes at Glasgow University over a period of years, and partly as a result of my own research on the effects of coloured haze or veiling glare. The tests in common use were only too obviously inadequate. Mr. Simpson, for example, could pass Holmgren's Wool test or the Edridge-Green Beads test with ease, but he failed the Stilling Tables unequivocally and the Ishihara test classed him as " totally green blind ". Dr. Haydock and Mr. McDonald, however, failed completely on all these tests, but the Ishihara and Stilling Tables did not discriminate them from Mr. Simpson. Dr. Haydock was, in daily life, much more able to discriminate colours and name them correctly than Mr. McDonald, but, again, the tests did not distinguish between their abilities. Hence it was clear that these three men had different degrees of defect which the available tests failed to differentiate efficiently. If the Holmgren Wool test had been the criterion Mr. Simpson would have been classed as " normal ", but it was obvious from his daily life that he had a marked defect. Had the Ishihara test been the criterion he would have been classed as " colour blind "; but it was clear that his defect was less than that of other men who would have been put in the same category. In the psychology classes several subjects, two of them women, had some difficulty with desaturated blue-green hues, but no existing tests gave unequivocal evidence of their defects. In the veiling glare experiments it was only too clear that the subjects varied in their sensitivity to spectrum colours in ways that the available tests did not decisively confirm.

In 1942 I mentioned my doubts to Dr. M. Collins, who fully concurred with my scepticism and advised me to take up the Rayleigh Equation as being most likely to lead to a decisive form of colour test. This led to the planning of a number of related experiments which are discussed in this book, and to the construction of the anomaloscope to be described later. Dr. Collins was most helpful, and I am grateful to her for many illuminating discussions in 1942 and 1943.

The third circumstance which tempted me to take the experimental study of colour seriously was growing difficulty with the Young-Helmholtz theory. Dr. R. A. Houstoun fully agreed with my

statement of the shortcomings of this theory in 1942. Much later I read his book and found his adaptation of the Hering Theory, which, in contrast with the Young-Helmholtz Theory, fitted the observed data with surprising efficiency. A secondary aim of the experiments then arose and became prominent: that of testing the principal theories of colour vision. At the start the Young-Helmholtz theory had been taken for granted, but became more and more doubtful because of its excessive simplicity in relation to the obvious complexity of the facts of colour vision. Experiments were then planned to submit this and other theories to critical tests. Thus the principal aims of the research came to be determined by the circumstances which led up to it. Other interests were added as the work proceeded, and the most important of these was the study of the inheritance of colour vision defects.

The whole research may be regarded as a preliminary study for a more detailed and adequate investigation of all the problems set forth, especially variations of colour vision with race, age, social status, intelligence, occupation and many other factors. The investigation of a planned sample, deliberately arranged according to the well-known principles of such studies, of not less than 10,000 men and boys and 10,000 women and girls, would be required to reveal the main trends of colour vision in a country the size of Scotland.

Before proceeding any further, I should like to make four points clear to the reader. In the first place, this book gives the results of tests all of which were carried out by the writer, with the exception of about half a dozen normal adults tested by Mr. Joseph F. Simpson and and the children tested by Mr. Robert Brown, and these children are not included in the group of subjects tested by the writer to standardise the Four-Colour Test.

In the second place, the temptation to alter the technique or details of the apparatus or set-up of the tests was resisted while they were in progress. Thus each "run" of tests has been made as consistent with itself in tester, technique, apparatus and experimental set-up as humanly possible.

Thirdly, I have also resisted the temptation to combine by statistical techniques the results of tests not strictly comparable on the psycho-physical side, in order to swell the numbers. Three exceptions to this rule will be found, however, which seemed justifiable. In experiments such as these, differences due to changes of coloured papers, filters, and details of laboratory technique, cannot be equalised or eliminated by statistical methods. If a subject appears as a major

defective in one test and falls into the normal group in another, then it is our task to find out what is wrong with either or both of the tests, and, for example, combined inter-correlations for such tests should be avoided.

Finally, I have tried to make it clear that statistics cannot replace the detailed study of the individual in psychology, but that statistical and individual studies are complementary. This science at its best consists neither of generalisations, whether verbal or mathematical, nor of individual observations, taken by themselves, but of all these combined and welded into a complete whole.

GLASGOW, AUGUST 1949

R. W. PICKFORD

INDIVIDUAL DIFFERENCES IN COLOUR VISION

Chapter 1

PROBLEMS OF COLOUR VISION

THIS chapter will be divided into three main parts. In the first part it will be necessary to give a short account of the characteristics of colour experiences and their relation to the physical stimuli concerned, and of other preliminary details about colour vision and colour blindness, for which the expert will forgive me. In the second part the four main hypotheses, which have been offered as explanations of colour vision, will be described briefly, because the book is concerned with experiments designed partly in order to test these hypotheses. The third part will deal with the Rayleigh Equation, upon which the experiments to be described later are based and modelled.

STIMULUS, RECEPTOR AND SENSATION

The normal stimuli which are capable of exciting vision consist of electro-magnetic light waves falling on the retina. Pressure on the eyeball and other exceptional stimuli may sometimes excite the retina to visual response, but these stimuli will not be considered in this book. Physical stimuli act by exciting the end-organs of the receptor systems. In vision these are the rods and cones of the retina, and most psychologists and physiologists accept the Duplicity Theory of von Kries, that the rods operate only in almost complete darkness, and give rise to colourless sensations, when the stimuli are far too slight to excite the cones at all, while the cones operate in brighter illumination and give rise to the sensations of ordinary daylight vision, at intensities of stimulation which are so great that the rods are now completely out of action. Willmer has put forward an interesting modification of this theory, namely, a suggestion that some of the problems of colour vision might be solved if we assumed the existence of certain " day-rods " which operate in bright light. For the purposes of the present book it will be best to accept the familiar Duplicity

Theory. Sometimes it will be convenient to use the expression " receptor system ", which includes not only the sensory end-organs but also their connections with the visual cortex of the brain. Much of the discussion about theories of colour vision is concerned with the number of receptor systems to be postulated in explanation of differential responses to the light rays of the visible spectrum.

The term sensation is a psychological word which applies to the conscious experience resulting from stimulation of the receptors under certain conditions. It has been suggested by physicists who are interested in colour vision that the psychologists have often confused sensation and stimulus, or perhaps even sensation and receptor system. Considering the amount of time which psycho-physicists have devoted to these particular distinctions during the last century, this suggestion is difficult to credit. It may be, however, that the psychologist seems to the physicist too anxious that the sensation should have adequate treatment. For example, a theory of stimuli and receptor systems which does violence to a major fact of sensory experience would seem to him scientifically inadequate.

The term response is often applied to the activities of the receptor systems as well as to the excitation of a sensation. Thus we can speak of a psycho-physical or psycho-physiological response, but we can also speak of behaviour as a response of the organism. The term reaction is largely equivalent to response, and is almost as difficult, though it is seldom or perhaps never applied to a sensation.

It will be seen from the present book that the psychologist's perspective is much oriented by an interest in sensations and con- scious experiences. He tends to look on the stimulus and receptor systems as leading up to them. Thence, of course, they lead also to behaviour, which is outside the scope of the present book, though speech and other forms of behaviour in the test situation are always our guides to the sensory experiences of the person being studied. In the same way the physicist's orientation is mainly towards the study of stimuli, and that of the physiologist is towards the examina- tion of the receptor systems. All are required in an adequate science, but these differences are clearly to be seen in Wright's and Willmer's delightful books. It is therefore not necessary that any excuse should be offered for the psychological orientation of the present work, and it is hoped that, after this preliminary comment on the use of the terms stimulus, receptor and sensation, the following discussions will be found clear without resort to complexities of language which might give the reader unnecessary trouble.

Hue and the Colour " Circle "

Most people with good colour vision agree that there is a complete " circle " of hue sensations, which, starting with red, proceeds to orange, yellow, yellow-green, green, blue-green, blue, violet, purple, magenta, carmine and so back to red. Edridge-Green[1] is probably exceptional in his claim that violet is not nearer in hue to red than is blue, but further away, and that the hues form a linear series and not a circle. Most observers will agree that violet is slightly more reddish than blue, and that the purples, including magenta and carmine, continue the series back to red. Indeed, carmine is usually classed as red, while there will be differences of opinion whether magenta is to be called red or purple, and violet is by many classed as blue. There is no gap in this circle from red round to red again for those with normal colour vision. For extreme red-green defectives it is generally claimed that there are probably two gaps, one in the neighbourhood of the greens and the other in that of the purples. Even if these gaps exist, they are not sharply defined, and they are occupied by greys faintly toned with blue or yellow. Although we use colour names as though the hues they designate were distinct entities, there is no sharp transition from one hue to another, but they merge evenly into each other all round the " circle ". They are like the points of the compass, and there is no more a definite change from red to yellow, for example, than there is from East to North.

Some people, to the surprise of Houstoun, are able to see indigo, a hue between blue and violet. I have always been able to see indigo, but both Houstoun[2] and Edridge-Green[3] say they cannot see it. Houstoun carried out an interesting experiment in which he convinced himself that it is a real hue to some people. Apart from indigo, about which there is some difference of opinion, the colour names mentioned above are those in common use and will be employed throughout this book. Yellow-green is by some people called lemon, and blue-greens are often divided into greenish-blue and blueish-green, while by Houstoun, at least, the true intermediate between blue and green is called peacock; crimson is a very saturated red probably falling between carmine and magenta.

All the colours from red towards orange and round to violet, including the extremes, but excluding the purples, magentas and carmines, are found in the spectrum which is formed by splitting white light into its component wave-lengths by a prism or diffraction grating. The corresponding wave-lengths of the electro-magnetic vibrations which form their physical basis are shown in Diagram I.

The hues covered by the terms purple, magenta and carmine are not found in the spectrum, but are formed by mixing red and violet, red and blue, or orange, red, violet and blue, in suitable proportions. They are not more complex in appearance than orange, yellow-green or blue-green, which correspond to unique light rays. Purple, magenta and carmine bridge the gap between violet and red with as much smoothness, from the point of view of sensation, as orange
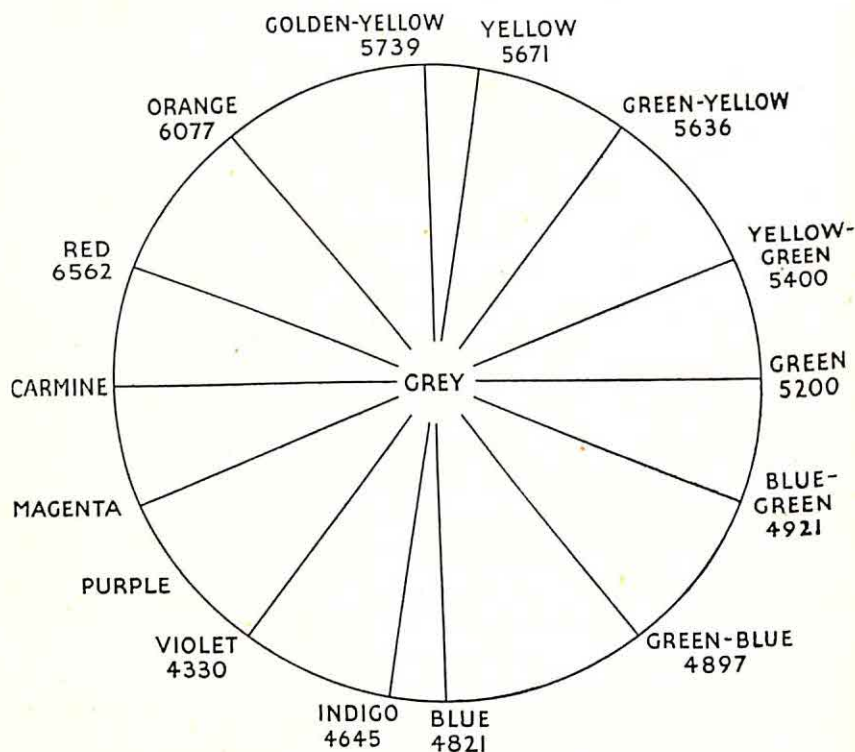
Diagram I. The " Colour Circle " showing complementary Hues spaced approximately

bridges the gap between red and yellow, or blue-green the gap between blue and green.

The " extra-spectral " and other intermediate colour sensations, however, are not so simple and elementary in appearance as pure red, yellow, green and blue. Orange may be described as reddish yellow; yellow-green as yellowish-green; blue-green as blueish green, violet as reddish blue; and the purples, magentas and carmines may be described as blueish reds. Great variety of tones, however, is found among all these colours. The terms red, yellow, green and blue, we

reserve for special hues, and Drever[4] has shown that there is considerable agreement in the choice of these by people with good colour vision. If we tried to describe yellow as yellow-greenish orange, green as blue-greenish yellow-green, blue as blue-greenish violet, or red as purplish orange, those with good colour vision would laugh, because of the unique simplicity of red, yellow, green and blue, which makes complex descriptions absurd. In addition, the tendency to exploit compound names for simple colours justifies our suspicion of colour vision defect. If a person is inclined to use the expression " reddish-green " for certain yellows he may be suspected of being partly red-green blind. On account of their simplicity and our inability to regard them as composed in any way of subsidiary or more elementary experiences, the four colours red, yellow, green and blue are known as psychological primaries. This, however, is quite different from asserting that they are physiological primaries for a theory of colour vision, but this will be discussed later. All these differences of quality, which enable us to arrange the colours on the colour " circle " from red to green and round to red again are differences of hue, but colours vary in other ways which will now be described.

BRIGHTNESS AND SATURATION

If an object reflects or transmits light we may speak of the intensity of light energy reflected or transmitted per unit area of the object. The intensity of stimulation of the retina, however, will be expressed in terms of the amount of light energy falling on it per unit area. Brightness is a subjective quality, and varies not only with the intensity of stimulation but also with the sensitivity of the individual and with the wave-length of the light rays which stimulate the retina. In general, brightness increases from red towards the middle of the spectrum and then decreases again towards violet. In daylight adaptation yellow-green will be the brightest hue; in dark adaptation greenish yellow will be brightest. This is known as the Purkinje phenomenon,[5] and is the result of the change from cone to rod vision, according to the Duplicity Theory. Variations of the brightnesses of different hues for large numbers of individuals in daylight vision will be discussed in more detail later, and certain conclusions will be drawn from their measurement. Many people use the term intensity for brightness, and reserve the term brightness for what is correctly called saturation. The Colour Group want to replace the term brightness by luminosity.[66] In colour vision tests it is usually necessary to follow the subject's own terminology even if the tester considers it erroneous.

Colour sensations held constant in brightness and hue may vary in saturation, a technical term for what might be called " colourfulness ". Some writers have called it brilliance, but this term is unfortunately confused too easily with brightness and is better avoided. A very full red or any other hue may be reduced in saturation by gradual replacement with grey, white or black. Its hue remains unchanged, and, if the colour is diluted with grey of exactly equal brightness for the observer in question, it will not change in brightness, but will become less and less saturated and end by being so dilute or desaturated that it is indistinguishable from the grey of equal brightness with which it is being diluted. If this experiment is done carefully, we can at this point cut off the grey light and show that some of the original hue still remains, though when mixed with the grey it is completely masked. If diluted with a dark grey or with black, a colour becomes less saturated and darkened at the same time; if with a lighter grey or white, it is desaturated and brightened at the same time. Saturation is much more rapidly reduced by dilution with white than with black. Often we use special terms for characteristic desaturated colours : orange diluted with black is called brown; red diluted with white is called pink, but many pinks are diluted magenta rather than red, and this is a matter of some interest to the colour vision tester, because it is characteristic of certain types of red-green blind persons to confuse pink with pale blue. Although very desaturated hues are generally called grey, strictly speaking the term grey is applicable only where hue is totally absent, and that usage will be followed here.

COMPLEMENTARY COLOURS

The rays of the visible spectrum of normal daylight are the components of white light, and if any section or sections of the spectrum are removed, then the remainder is complementary to them, because taken together again they would form white light. There is no sense in which one group of stimuli can be said to be complementary to another except in relation to vision. They are complementary only because they excite receptor processes as a result of which, in combination, the sensory differences of hue which would arise if they were taken separately, are eliminated. For instance, if the blue and violet rays are removed, then that group will excite blue and the remainder yellow sensations, but these two sections, blue and yellow, taken together, will again be white. The explanation of the artist's method of making green by mixing blue and yellow will be given later.

The principle of complementaries will work in a narrower sense.

For any wave length we may find another which, when mixed with it in appropriate proportions, can excite a grey or white sensation. We can use a mixture of rays corresponding to an extra-spectral hue, such as magenta, as one of the units in such an experiment. Then, of course, there will be three groups of wave lengths involved, but only two hues. Though this is really an example of three colour mixing, to be discussed later, it is usefully mentioned at this point.

The colour circle is usually arranged so that complementary hues are opposite to each other. Thus in Diagram I spectrum red is complementary to blue-green, orange to greenish blue, yellow to blue, greenish-yellow to violet, yellow-green to purple or magenta and green to carmine, (see Table 1). Spectrum red is not complementary to green, but yellow and blue are exactly complementary. A carmine which is complementary to pure green can be made by adding violet to spectrum red, and this carmine sensation is a purer red and a better psychological primary than the spectrum red often chosen.

TABLE I

COLOURS, COMPLEMENTARIES AND WAVE LENGTHS

Colour	Wave length in Ångstrom Units	Comple-mentary	Wave length in Ångstrom units	Ratio of Wavelengths
Red	6562	Blue-Green	4921	1·334 : 1
Orange	6077	Blue	4897	1·240 : 1
Gold-Yellow	5853	Blue	4854	1·206 : 1
Gold-Yellow	5739	Blue	4821	1·190 : 1
Yellow	5671	Indigo	4645	1·221 : 1
Yellow	5644	Indigo	4618	1·222 : 1
Greenish-Yellow	5636	Violet	4330	1·301 : 1

Table 1, showing certain colours with their wave lengths and complementaries, is quoted by Edridge-Green [6] after Helmholtz, and it shows not only the complementaries, but the wave lengths to which he attributed certain colour names, and the ratios of the wave lengths of these colours and their complementaries. These ratios are always in the neighbourhood of 1.2 to 1.

Wave Lengths of Spectral Colours

A simple laboratory experiment may be carried out for determining the central wave length to which a given colour name is applied by any individual tested, and the limits within which that name is applicable by him. The subject observes the spectrum of white light through the eye-piece of a spectrometer, and, starting at the extreme red (or violet) end, he reports the colour he sees to the experimenter, who records his observations, noting the wave length corresponding to each statement, and moving the spectrum slowly round until the other end is reached. Edridge-Green used the spectrometer as his principal apparatus for studying colour vision. He says that it is better to start in the middle of the spectrum and work out towards the extremes. No doubt both techniques should be combined for a satisfactory experiment, and several repetitions will enable the experimenter to find the mean point of change from each hue to the next and to work out the mid-points of the hues for the subject in question.

Table 2 shows the central wave lengths in Ångstrom units for the eight most commonly named colours, measured on eight subjects who were experienced in colour vision experiments. Subject 3 in this experiment was " green anomalous ", having a form of red-green defect which will be fully explained later in the book. This defect, though clear and consistent in tests which will be described later, does not show at all clearly in the spectrometer experiment. His only marked peculiarity here was his failure to mention the presence of blue-green. This subject would almost certainly be failed in a

TABLE 2

Central Wave Lengths of Colours for Eight Experienced Subjects

| Colours Observed | Subject's numbers and Central Wave Lengths in Ångstrom Units | | | | | | | | Variation | |
	1	2	3	4	5	6	7	8	Limits	Range
Red	6600	6600	6500	6500	6600	6600	6600	6600	6600—6500	100
Orange ..	6250	6180	6140	6000	6230	6010	6060	6120	6250—6000	250
Yellow ..	6050	5940	5710	5660	5890	—	5930	5890	6050—5710	340
Y-Gr. ..	5870	5870	5560	5100	5800	—	5810	5700	5870—5100	770
Green ..	5650	5200	5390	5000	5650	5760	5670	5530	5780—5000	780
B-Gr. ..	5000	5060	—	4900	5060	5200	4870	5180	4870—5200	670
Blue	4670	4880	4800	4800	4850	4950	4740	4940	4950—4670	280
Violet	4530	4680	4300	4300	4780	4420	4540	4420	4780—4300	480

serious clinical test of red-green vision, but the spectrometer does not reveal his essential weakness. This shows that it cannot be used as a universal method of detecting colour vision weaknesses, as Edridge-Green hoped. Subject 6, who failed to name yellow and yellow-green, proved in other tests to have a decided weakness in yellow-blue vision, for him affecting yellow more than blue. For the other six subjects there is moderately good agreement. The ranges within which these central points vary for the eight subjects are shown in the last column. The order of variability of the colours is red (least), orange, blue, yellow, violet, blue-green, yellow-green and green (most), for this group of subjects. If there is any general tendency shown by this variability it is that the colours at the extremes of the spectrum are least and the colours in the centre of the spectrum are most variable. This experiment is much too dependent on colour naming to be used as an accurate method of assessing individual differences in colour vision. If it must be used, however, the experimenter must not on any account volunteer the name of any colour which he may think the subject has overlooked, or say the name of the colour with which he is working or correct the subject in any way whatever about the use of names.

Colour Mixtures

When two complementary colours are mixed, there is complete loss of saturation : the result is a colourless sensation of brightness intermediate between the two original hues. When two colours which are not complementary are mixed an intermediate hue on the colour circle is produced with loss of saturation roughly proportional to the distance apart of the original hues on the colour circle. Brightness is again intermediate. Red and green when mixed form a desaturated yellow, but the loss of saturation is only moderate when we compare the mixture with spectrum yellow which is already a weakly saturated hue. The very saturated yellows of daily life are usually produced by mixtures of red, orange, yellow-green and green rays all added to yellow itself. Yellow-green and blue-green when mixed form a rather desaturated green, and in the same way blue-green can be matched with a mixture of blue and green, though again with loss of saturation, and violet can be matched by adding red to blue. In this way any hue, whether one of the familiar primaries, red, yellow, green, and blue, or not, may be imitated, but always with loss of saturation. Since two colours may be found which are complementary, and since either of them can be imitated with two other colours mixed, three

colours may be found such that one of them is complementary to the other two. This may be done whether we start with one of the primaries or not, and it is the basis of the famous theories of three-colour mixing which led to the Young-Helmholtz or three-colour theory of colour vision. If we take three stimuli, such as a slightly orange red, a slightly yellowish green and a slightly violet blue, all colours in the circle may be imitated in hue by appropriate mixtures of them, but not completely in saturation.

Many brilliant experiments, such as those by Maxwell, König and Dieterici, Abney, Houstoun and Dow,[7] Wright and Guild, have been carried out to test the hypothesis that all colours may be matched perfectly both in saturation and in hue by mixtures of three stimuli, and extremely accurate measurements of the mixtures required have been made. Houstoun, however, points out what is also admitted by Abney,[8] and discussed at length by Wright,[62] that in the strictest terms it is open to doubt whether these experiments have succeeded. It is always possible, of course, as Abney supposes, that the difficulties are due to inadvertent faults of technique and apparatus, particularly the entry of stray white light. Considering the immense care which Wright has lavished on these experiments, however, this is the least likely explanation. We must therefore give some attention to the difficulties of the trichromatic matching experiments.

Trichromatic Equations

Houstoun[9] explains what is widely accepted and is discussed in detail by Wright, that these tricolour mixing experiments work perfectly if we are allowed, when necessary, to superimpose one of the primaries in use upon the colour to be matched. This will, of course, desaturate it to the necessary degree, and the primary so used will appear in the tricolour equation as a negative. For example, the sensation produced by a stimulus of homogeneous blue-green rays must be desaturated slightly with the red primary stimulus before it can be matched by the sensation produced by the blue and green primary stimuli combined. This may be represented in the following way:—

$$P \text{ Blue-green} = Y \text{ Green} + Z \text{ Blue} - X \text{ Red}$$

Also we shall have :—

$$Q \text{ Yellow} = X' \text{Red} + Y' \text{Green} - Z' \text{Blue}$$

and :—

$$R \text{ Violet} = Z'' \text{Blue} + X'' \text{Red} - Y'' \text{Green}$$

Not only " minus " red, but also " minus " green and " minus " blue stimuli are required in small quantities in matching appropriate parts of the spectrum. The process looks rather like balancing bank accounts by introducing negative investments. The negative balance of any primary stimulus required in a colour match, however, is simply a measurement of the extent to which the other two when mixed fail to reach the saturation of the colour to be matched.

Wright[62] has pointed out, in an extremely interesting discussion of this subject, that there is no difficulty in selecting a set of primary or " reference " stimuli which will yield all-positive versions of the tricolour equations in which the negative values appeared. It is merely a question of employing appropriate algebra. In doing this, however, we are forced to utilise reference stimuli which have no physical existence. This has been pointed out by other writers, such as Houstoun, and it is one of the things to which Drever has taken exception.[4] Wright explains, however, that it can be understood as meaning that no physical radiation is capable of stimulating one of the receptor systems without causing activity in the others. " We can imagine," he says, " that each of the receptor systems acting alone would give rise to a sensation more saturated than any which we normally experience under ordinary conditions of observation." This is the effect of the over-lapping of the receptor systems.

In consequence of these researches it must be understood that the colour triangle used to represent colour mixing by the earlier writers, and constantly employed in lectures and demonstrations, does not represent the facts. The sides of the triangle must be allowed to bulge out in one direction or another, unless, as Houstoun explains, we employ primary stimuli which are not located on the triangle them-selves—these are the " imaginary " colours mentioned by Drever, which exist only in the algebra of the colour triangle and not in real experience. If we keep to real rather than to imaginary reference stimuli, however, the " triangle " given by most workers bulges out heavily on the blue-green side, but by a selection of reference stimuli more closely corresponding to the unanalysable primary colour sensations, it might be made to bulge out on the yellow side instead. Then it would tend to the form of a quadrilateral figure with prominent angles for red, green and blue stimuli, and a less prominent angle for yellow. This relative weighting will be found to accord with the evidence to be given later, that a yellow primary is required, but is of relatively less importance than those for red and green. In fact, to anticipate for a moment, it would appear that normal colour vision is mainly controlled by the red-green system, and the yellow-

blue system plays a subsidiary part, whereas in the colour vision of major red-green defectives the red-green system is so much reduced in efficiency that it becomes of less importance than the yellow-blue system. This is why they seem to be dichromatic.

To return for a moment to the primary sensations of special interest to the psychologist, he would like to see simplicity of sensation made to correspond as far as possible with simplicity of receptor-system, especially in colour vision, in which the simplicity of certain sensations is sharply contrasted with the complexity of others. It seems impossible that this could be done on the trichromatic theory, but, if the theory were perfectly satisfactory in other ways, the requirement that simple receptor systems should correspond to simple sensations might be one which we should be forced to relinquish.

Drever[10] has drawn attention to the difficulties of tricolour schemes, and has suggested that every attempt at a three-colour theory has tacitly assumed the equivalent of four primaries. We may look on the problem in another way. Minus red, for example, is not red at all, it is blue-green. Minus blue is yellow and minus green would probably be violet for the yellowish green primary employed. Blue-green, yellow and violet do not appear among the most favoured tricolour primaries, which are slightly orange red, yellowish green and violet-blue. The experiment in which minus red, green and blue appear therefore strongly suggests not three but six colour mixing, because we appear to be manipulating six possible receptor systems : red, yellow, green, blue-green, blue and violet. Indeed, if violet is not complementary to the yellowish green primary, then an additional process will be implied which corresponds to the use of a seventh primary which is redder than the orange-red of tricolour mixing, and we shall possibly have red, orange, yellow, green, blue-green, blue and violet. We shall see later that it is not without interest to consider the possibility that tricolour mixing experiments might support a heptachromic theory of colour vision[12]; that the trichromatic theory is not proved by these experiments but actually thrown into doubt. Seven primaries, however, are probably too many, and an arrangement of four, as suggested above, would be most satisfactory.

Göthlin[11] has suggested that the unavoidable negatives might be accounted for in terms of inhibition. For example, in the tricolour matching experiments, when the blue-green of the spectrum is matched with a mixture of blue and green, this pure blue-green might have a negative effect on the red response system. Hence the blue-green mixture is less saturated than the pure blue-green itself and

some red must be superimposed on the blue-green to be matched before a satisfactory equation is obtained. Since all colours are produced by combinations of fundamental sensations in appropriate proportions, however, this means that " an impulse for a colour sensation of whatever quality releases to some extent an inhibition for the complementary colour within the same area ".[11] In order to show that blue-green has more inhibiting effect on red than blue and green mixed, we must grant it a special negative function. This principle must be extended to the other receptor systems. The red receptor now becomes a negative receptor for blue-green, the blue a negative receptor for yellow and the green for violet. This detracts considerably from the simplicity of the trichromatic theory, which was a valuable feature, and even suggests the balanced systems of receptor function in the Hering theory, while the number of processes involved might now be too many rather than too few.

If we do not allow the assumption that each primary function may have the capacity of " negative " reception for the pure or homogeneous rays of its complementary colour, then it is difficult to see how the concept of inhibition can help us at all. The mixture of blue and green, as Göthlin points out, would excite the same receptor systems as the homogeneous blue-green rays, and any negative response tending to desaturate the sensation produced by the mixture would affect the other sensation in exactly the same way. Unless the loss of saturation can be regarded as due to the tendency of each stimulus to excite all receptors, therefore, it must be due to a fourth primary which is not being represented in the tricolour equations except as a distribution of negatives. Once again, if we re-arrange the primary stimuli to correspond more nearly with the primaries of sense experience, namely, red, green and blue, instead of a slightly orange red, yellowish green and violet-blue, then the negative quantities will collect in the direction of minus blue, which is yellow, and would be a fourth primary.

Four-colour matching experiments have never been done so carefully as three-colour experiments, if at all, but it is an important possibility that they might support a four-colour theory more efficiently than the existing experiments support a three-colour theory. The use of negative colour-stimuli might be avoided, and minus blue could be called by its real name viz. yellow. It would be worth while, therefore, to perform these experiments with as much care as has been lavished on the tricolour work, to find out whether all colours could be matched in saturation as well as in hue with four primary stimuli. If the negatives could not be eliminated even then,

we might be forced to think of five primaries or even more.[12] From a scientific point of view it would be very much worth while to know how many primary stimuli were required by subjects of normal and various kinds of defective colour vision, in order that the negatives should be eliminated.

PRIMARY COLOURS

Now it will be necessary to review the subject of primary colours more carefully. Such colours may be defined " physiologically ", as those which change least in hue in peripheral as compared with central vision, and in different degrees of intensity; they may be defined psychologically, as those which are unanalysable, pure or simple in sense experience; or they may be defined as those physical stimuli which are most successful in colour mixing to form all intermediate hues. Table 3, compiled partly from Drever,[4] Houstoun,[13] Wright,[62] Göthlin,[11] and from the Ilford[14] and Wratten[15] Colour Filter Booklets, shows the relationships between these different groups of primaries. It includes the Ilford and Wratten standard monochromatic filters. The physiologically stable red is not in the spectrum, but it is represented by five experimenters as complementary to 4940, which is very close to the green primaries of most observers. The psychologically pure red is not far from the primary red of tricolour mixing experiments. These reds are faintly orange, however, and the physiologically stable red is no doubt a psychologically purer primary than the spectrum red of about 6500 usually chosen. The physiologically stable greens tend to be less yellowish than the tricolour green primaries, and so do the psychologically pure greens of Drever and Pickford. The mean for eight subjects, 5481, however, is nearer to the tricolour greens. This mean reading, however, is not to be regarded as a better estimate merely because it is an average for eight subjects. These subjects were experienced, but not so expert as the workers who chose a green of the order of 5050 as purest or most stable. In addition, it was known that at least two of them had small abnormalities of colour vision. Unless special precautions had been taken to include in the average an adequate sample of random variations, that average should be discredited, and the individual readings are to be preferred. All the physiologically stable and psychologically pure blues are less violet than the blues of tricolour experiments. The Ilford monochromatic filters correspond well with the physiological and psychological criteria. The Wratten monochromatic series includes neither yellow

TABLE 3

WAVE LENGTHS OF PRIMARY COLOURS

Class	Authority	Ångstrom Units			
		Red	Yellow	Green	Blue
Physiologically Stable	König	Complementary to 4940	—	5050	4700
	Exner	Same	—	5080	4750
	Goldmann	Same	5750	5050	4680
	Schubert	Same	5750	5030	4680
	Hess	Same	5745	4950	4710
	Baird (Mean)	Same	5690	4915	4610
Psychologically Pure	Drever (Subj. 1)	6500	5620	5050	4720
	Drever (Subj. 2)	6500	5690	5120	4720
	Pickford	6500	5660	5000	4800
	Pickford (Mean for 8 subjects)	6575	5867	5421	4829
Used in Tricol. Expts.	Maxwell	6300	—	5280	4570
	Wright	6500	—	5300	4600
	Guild	7000	—	5461	4358
	Houstoun	End to 5800	—	6500—4800	5400 to End
Colour Filters	*Ilford* : Tricol.	End to 6100	—	6100—4800	5100—3700
	Monochr.	End to 6250	6100—5600	5450—5000	5200—4450
	Wratten : Tricol.	End to 5800	—	6500—4800	5400 to End
	Monochr.	End to 6500	—	5700—5100	—

nor blue, but has yellow-green and violet-blue instead. Its green is too yellowish.

On the whole, therefore, we may say that there is agreement that the most stable and the purest primaries are : red complementary to 4940; yellow, about 5700; green, about 5050; blue, about 4750. It is therefore not unlikely that exactly complementary pairs could be chosen, if we are allowed a slightly carmine sensation as a primary red. With four stimuli the requirements of matching all colours in both hue and saturation by appropriate mixtures would probably be satisfied better than it is with the three usually chosen for that purpose. The psychologically pure red sensation would, however, always be represented on the stimulus side by a mixture of some blue with the red light rays.

MONOCHROMATIC AND POLYCHROMATIC COLOURS

The colour sensations in everyday life, with the exception of spectrum colours, as in the rainbow, for example, are not simple in physical basis, but are excited by groups of wave lengths or bands of spectral colours mixed together. Thus ordinary saturated yellows usually consist of as much red, orange and green as of yellow, while pure spectrum yellow, which is not mixed in this way, is much less saturated. Greens usually contain yellow, yellow-green, blue-green and even a distinct band of red as well as green itself.

If a colour contains hues mixed in the way described, it is polychromatic, If it contains only a single narrow band of wave lengths, so narrow that no difference in hue can be detected in passing from one side of the band to the other when it is seen in a spectrometer, then it is monochromatic. In the construction of monochromatic colour filters, which are in common use for colour vision experiments, a certain amount of liberty is allowed. A filter which complied rigidly with the criterion given above would necessarily cut down the incident light very severely and transmit only a very small fraction of it. Such a filter would be very dim, unless illuminated from an extremely intense light-source. In practice these filters are made to transmit a small amount of the neighbouring rays, which is little enough to make no significant difference to their essentially monochromatic quality. The coloured papers commonly used in psychological laboratory experiments, like the majority of colour filters, are not in the least degree monochromatic.

From this discussion it is clear that monochromatic colours always reveal in appearance their essential composition—they look what they are—but, without spectroscopic analysis we do not know that they are monochromatic. Many polychromatic colours also reveal their composition in appearance : purple looks both reddish and blueish, for instance; but again spectroscopic analysis is required to prove exactly what components are present. Where complementaries are present, however, the appearance of a colour may be no guide to its physical composition. A yellow may contain all the colours of the spectrum except blue and violet. The reds, oranges and blue-greens simply neutralise each other and add nothing but brightness to the mixture. A green may contain all colours except oranges—even red is present in most greens. Finally, greys and white are composed of wave lengths each of which is completely desaturated by its complementary. Thus white light may be a mixture of all visible wave lengths, but excite a psychological sensation from which all

colour has been withdrawn because each of its components is fully desaturated. The addition of a small amount of any colour to this mixture will then tilt the balance in the direction of the colour added. The subtraction of a small amount will tilt the balance away from the colour subtracted. If red be added to white (or grey or black) it will become faintly pink; if red be withdrawn it will become faintly blue-green.

PIGMENTS, DYES AND FILTERS

Opaque objects may reflect light rays of various wave lengths in the proportions in which they are incident in white light. Then the objects will be white. If, however, they reflect some of the rays more freely than others, they will be coloured accordingly. Objects not opaque, similarly, may transmit the light rays in the proportions in which they are incident in white light, when the objects will be white if translucent, or colourless if transparent. When, however, the transparent or translucent object changes the proportion of the incident wave lengths in transmitting them, it will be coloured accordingly, and is a colour filter, because it filters out certain colours.

Pigments are made of finely divided opaque, transparent or translucent substances, held in suspension in a medium and forming a coloured surface which adheres to the object in question. Dyes are substances which are held in solution in a transparent medium and act as colour filters; or they may saturate the substance coloured and filter the light reflected from its surface layers. Paints in common use may be chiefly reflecting, like gold and silver or aluminium paint; they may be suspensions of transparent particles, or they may be transparent solutions which dry and form layers of surface colour filter. Light reflected from the surface may be filtered in passing through the paint; and/or light may be coloured by reflection from the suspended particles. A substance may have one colour when it reflects and another when it transmits light, like gold leaf, which is yellow by reflected and red by transmitted light.

In the mechanics of colour mixing there are many complexities, some of which are worth attention here because colour mixing is of great importance in the experiments to be described in later chapters. If we place one or more colour filters together, their combined effect will be subtractive : only those rays will pass which are transmitted by both or all of the filters. Thus if we take two filters whose transmission bands overlap widely, like a polychromatic yellow and blue, the remainder transmitted by both will be green. The green is not a mixture of yellow and blue, but is simply the colour which passes

both filters. This is, in general, the way paint-mixing works. Paints act chiefly as colour filters for the light which is incident, and is reflected, either by the white paper beneath, if they are water colours, or by the white reflecting particles incorporated in the medium in the form of Chinese white, if they are oil colours. There must be green in the yellow and blue if it is to be left over when they are mixed. In mixing opaque pigments and in combining finely divided reflecting surfaces to mix colours, of course, the effect is additive, not subtractive, and the actual combination takes place in the eye according to the laws of colour mixing. Here again, a green may be produced by mixing yellow and blue, but it will be desaturated with the grey produced by the blue and yellow as complementaries, which, in this case, are not filtered out. Combined filters of complementary colours and of other colours whose transmission bands do not overlap, will be black because taken together they are opaque. A mixture of finely divided reflecting surfaces which are of complementary colours, or which are white and black, will form a grey in combination.

In colour mixing experiments we have to consider what combination of light rays will be brought together upon the same retinal area, and to adapt the apparatus accordingly. The two common methods of colour mixing are : (a) by rotating disks or prisms which throw colours upon the same retinal area so quickly in succession that a fused effect is produced; (b) by means of lenses, prisms or mirrors, which throw separate beams of light upon the same retinal area at the same time. Both the lens and the rotating disk methods have been used in the experiments to be described in the following chapters, but chiefly the method with lenses.

It is perhaps worth mentioning the use of negative colour names by manufacturers of colour filters.[66] A " minus " red, green or blue colour filter is one which transmits all rays except those which make up red, green or blue, as the case may be, and is, accordingly, complementary to those which it excludes. Thus a " minus " red filter is simply one which is opaque to rays making up red, and similarly for the others.

MIXING POLYCHROMATIC COLOURS

For many practical purposes, as in colour printing and photography, the principle of three-colour mixing is apparently quite satisfactory. Indeed, as Houstoun points out, these practical processes have provided a model which convinces many people of the truth

of the trichromatic theory. It is therefore worth considering why they do not in fact give it any support whatever.

In these processes the " primaries " employed transmit or reflect wide bands of wave-lengths which divide up the spectrum between them. This is clearly seen, for instance, in the " Colorscope ", an instrument recently produced in America, in which varying intensities of illumination of three lamps, a red, a green and a violet-blue, are manipulated to make a mixture which matches a white light. This is a most valuable and instructive apparatus, but it does not prove the trichromatic theory. It merely proves that white light may be made by mixing all kinds of light rays in the required proportions. Another set of lamps, namely, orange, blue-green and violet, could be made which would work equally well. It is not necessary to have three lamps. A suitably constructed pair of lamps would be perfectly satisfactory. All that is then required is that they should be complementary. It is not even necessary that they should produce, between them, all the light rays of the spectrum—this will be evident from what has been said before about complementary colours. It is not clear to everybody that a white light may be made which is grossly lacking in certain components of the spectrum. This is the reason why certain types of fluorescent white lighting are completely useless for picture galleries and shop lighting when colours have to be appreciated, chosen and matched.

In colour mixing with polychromatic primaries, however, it is not necessary that our experiments should be limited to three colours. White light can be matched with four, five, six or any number of primaries. Where polychromatic lights are used three is neither the smallest nor necessarily the best number to employ. The implication of this for colour printing and photography is obvious. A three-colour process is more efficient than a two-colour process, but the more colours we add the better the result until we reach a limit of practicability. Three, however, is the smallest number which is likely to give a result which is not too crude by a process which is not too difficult.

One further thought on this subject will occur to the reader, and it is the question why in making colour matches with polychromatic primaries we do not need the negatives discussed in a previous paragraph. For instance, by the method of the colour-wheel we may combine the light reflected by a blue and a green paper and match a blue-green without superimposing red upon it. The reason for this is that the negative red stimulus is already present by implication. A spectroscopic examination of the polychromatic coloured papers

will reveal either that the blue-green paper reflects enough red light to be sufficiently desaturated to be matched by the others, and/or that the blue and the green papers between them reflect enough blue-green rays to be sufficiently saturated to match the blue-green paper. The same general principle applies for other polychromatic mixtures.

After Sensations and Contrast Effects

When part of the retina is stimulated for some time with a given patch of colour an effect is produced which takes the form of a slight reduction of brightness and saturation of the colour while fixated, and, when the stimulus is removed, a coloured after-sensation exactly corresponding to the area of the retina stimulated. This after-sensation is in the complementary colour of the stimulus, and gradually fades with characteristic fluctuations. In the same way a dark after-sensation is produced by a bright stimulus and a bright after-sensation by a dark stimulus. These after-sensations have an important bearing on theories of colour vision. They have been explained as contrast effects, as the result of fatigue of retinal processes, as spontaneous readjustments of retinal functions towards the resting condition after stimulation, and they might be produced in other ways of which we know nothing. They are complementary in colour to the original, and they start forming from the very moment of fixation, because the loss of saturation and brightness represents the effect of the complementary after-sensation already being formed. The intensity of the after-sensation increases the longer the fixation of the stimulus. Another form of after-sensation is the same colour as the stimulus, and is produced after momentary fixation. It is very fleeting and is difficult to observe. The complementary after-sensation is called " negative " and the other " positive ".

When a colour stimulus is set alongside a grey, especially when the line of division is blurred, the grey tends to take on the complementary colour of the stimulus. This effect is called simultaneous contrast or induction, and is usually more evident if the grey is darker than the colour stimulus. This is because the simultaneous contrast effect adds colour to the grey, and the grey desaturates this colour. Dark greys are much less effective in desaturating the hue of a given colour than bright greys or white. In the experiments described later it is frequently necessary to be sure that two patches of colour are equally bright before the subject can say that there is no colour difference. If one is darker, a colour difference which is imperceptible between equally bright patches will be enhanced by simultaneous

contrast and become perceptible, since the darker then seems to change towards the complementary of the brighter patch. Simultaneous contrast also takes place between two coloured patches. A colour always looks specially saturated when set close to its complementary, and this effect is increased if the dividing line is blurred. The effect is also found when a dark patch is set beside a bright patch, the dark becoming darker and the bright one brighter by simultaneous contrast. All such contrasts are systematically exploited by artists to obtain enhanced saturation, darkness or brightness.

The formation of what will subsequently form a negative after-sensation decreases the saturation of any coloured object, such as a picture, if fixated steadily. Therefore frequent changes of the fixation point will tend to enhance its brilliance. At the same time this brilliance is also enhanced by the presence in close proximity of patches or spots of complementary colours. The *pointillist* painters attempted to imitate the brilliance of light by using spots of complementary colours so closely juxtaposed that we tend to see a combined effect in many instances, rather than a mass of dots. The brilliance they produced in this way was due to their unintentional exploitation of simultaneous contrasts between all the numerous spots of colour. In addition, they gave the observer a great number of closely placed alternative fixation points, movement from any one of which almost imperceptibly to its neighbour would change the " mosaic " of colour stimuli over the whole area of the retina on which the picture was projected. In this way loss of saturation owing to continued fixation of the same hue was largely overcome. The speckled effect of *pointillist* paintings is therefore often specially brilliant and luminous, although the pointillist technique does not in the least degree imitate the true nature of light.

Black, White and Grey

The extremes of white and black are joined by a series of neutral greys which may be called colourless tones or hueless colours, according to the terminology we prefer. The greys in use in everyday life are often simply near-greys and have in fact some hue, though very slight, but, strictly speaking, the term grey is applicable only when there is no perceptible hue whatever. White is produced by mixture of all the colours in the spectrum in the proportions found in daylight, but it is not in any sense in possession of hue itself. White may be called a colour, but it cannot by any stretch of imagination be described as a reddish-orangeish-yellowish-greenish-blueish-

indigoish-violet. It is distinct, unique and unanalysable. It is not the negation of hue in experience, but is positively white. Similarly, though greys can be made by desaturating colours with the necessary amounts of their complementaries, grey is lacking in hue itself. Grey is not, for example, a reddish-peacock, a greenish-carmine or a blueish-yellow. By looking at a grey we cannot tell without spectroscopic analysis out of what mixture of complementaries it was formed. Black is also a quality of unique and positive character, though it has no hue, and, although many people think black is just the absence of light stimulation, real black can be produced only under special conditions, as when visual stimulation is suddenly cut off, or by sharp simultaneous cortrast, or when we look into the shadowed entrance of a deep box lined with a totally non-reflecting surface, such as black velvet. White cannot be called a brilliant black, nor can black be called an absolutely dark white; but greys can, in general, be called whitish-blacks or blackish-whites, just as orange can be called a reddish-yellow. Consequently it is necessary to think of white and black as primary qualities of sense experience, while greys must be regarded as intermediates between them.

Abnormalities of Colour Vision

Like every other human psychological and physical condition, ability, trait or feature, colour vision is subject to variation from one person to another. In general, variations of human characteristics and abilities tend to be normally distributed; that is to say, if a very large number of individuals are measured for a given characteristic, there are many intermediates and few extremes, and the graph of this distribution forms a smooth and bell-shaped curve having certain mathematical qualities which will not be discussed here. Variations of a characteristic which fall within the limits of such a normal curve can be called normal variations, though some of them are sufficiently extreme to warrant special attention as being very unusual. Any variations which fall outside the limits of the curve will then be abnormalities, and must be accounted for by some special cause other than the causes of the normal variations. Where there is a fair proportion of extremes which fall decidedly outside the normal curve of variations of a given characteristic, we speak of discontinuous variation, and this is the condition found in human colour vision, which will be dealt with in detail later.

Some illustrative examples of abnormal colour vision may now be given. There are several forms of the defect called red-green blindness.

An educated man, for instance, has what he calls a difficulty in naming certain colours. He thinks he has failed to learn to use the names red and green correctly. All his friends know that he is frequently unable to find a red golf tee when it is lying in the green grass. Yellow and blue tees are always perfectly clear to him. He buys a brown suit of clothes under the impression that it is green, but attributes his mistake to bad lighting in the shop; nevertheless, he is confused over his suitcase in a railway station and finds himself at home with a green one belonging to another man, under the impression that it is his own brown case.

If we make this man submit to carefully planned colour discrimination tests, in which he first matches the colours to be distinguished for brightness, so that there is no possibility of his guessing that a brightness difference implies what he knows another person would call a colour difference, and, if in testing him we rigidly avoid the use of names of colours, and do not betray by a smile or gesture any mistake which he may make, then he is found to be quite unable to distinguish red, yellow and green, although the colours we call red he regards as slightly more saturated than the other two which are nevertheless of the same hue to him. Yellows and blues he can distinguish readily, but he is not good at separating desaturated yellows or desaturated blues from greys of exactly their own brightness. Purples, violets and blues he calls uniformly blue, without discrimination of hue, though violet and purple are less saturated for him than blue. This is an extreme form of red-green blindness, with added weakness in yellow and blue.

Another man congratulates a lady friend on having had her old coat dyed such a fine black. She is indignant: it is neither old nor black, but is new and crimson. In a quiet conversation, after all his anxieties and defences have been laid aside, and after he has made friends with the tester, this man admits that black would be quite a good term to apply to the colour of ordinary pillar-boxes, though of course, he always agrees with everybody else that they are really red. When systematically tested, with all the necessary precautions in the avoidance of the use of colour names and in minimising brightness differences, he was sometimes able to distinguish dark grey from an equally dark red, but with considerable difficulty. He was unable to distinguish either red or green from yellow of equal brightness, but, if the brightness was not controlled, he was able to distinguish them easily because for him yellows are bright, greens dimmer and reds very dark. He has no weakness whatever in distinguishing yellows and blues from greys of equal brightness, but all purples and violets

he calls blue indiscriminately. This man has an extreme form of red-green blindness in which the reds are greatly darkened, but he has no yellow or blue weakness.

A third subject was not aware of any difficulty with colours until he failed in a test for the R.A.F. In this test he once mistook fawn for green, and was very annoyed at being rejected. In the laboratory he spent five minutes trying to make quite sure that a green and a fawn skein of wool were not the same colour. Losing patience a little, I asked him what his difficulty might be, but he replied that he had no difficulty and was merely trying to be very exact. I explained to him that if in five minutes he had been trying to be very exact over the colour of a green signal at night in a fog, he might have crashed his aircraft into a hangar and killed a number of people. He does not believe that he is colour blind, but has a marked difficulty in distinguishing reds and greens from each other and from yellows, when there are no brightness differences, though he has no weakness in blues or yellows. This is an example of moderate red-green blindness, and this sort of man is liable to call certain fawn or yellow-ish colours " reddish-green ". He would not be failed in a colour vision test with any injustice, however, because his sensitivity to the difference between red and green is at least ten times less than that of 90 per cent. of men.

A fourth subject, a minister in the Church of Scotland, had known most of his life that he had a difficulty with greens. He was asked to do Edridge-Green's Beads Test, in which the subject has to pick out all the red, green, yellow and blue beads in turn from a selection of about 50 beads of varied colour, shape and size. The colours are taken in turn, and each bead chosen is placed in a hole with the appropriate name printed below it, and through which the bead vanishes from view and cannot afterwards be a guide to others chosen. The experimenter watches with a poker-face and refuses to answer any questions whatever. This subject chose red beads correctly, included blue and green indiscriminantly in the green hole, put only orange in the yellow hole, and placed both green and blue in the blue hole. He left the yellow beads on the tray, saying that they were white. In more detailed tests he proved to have a very small red-green weakness, hardly beyond the limits of normal variation, but to have great difficulty in distinguishing either yellows or blues from greys matched carefully with them in brightness. He is very yellow-blue weak, but is able to distinguish these colours from greys if they are sufficiently saturated or sufficiently different in brightness.

A fifth subject has no difficulty with ordinary tests of red-green

blindness, but cannot do any physiological estimations with a colorimeter in which yellows are involved. If he attempts to do such tests he makes successive estimations which differ as much as 30% from each other. He proved to be weak in blue and very weak in yellow. A sixth subject told me that his wife laughed at him for confusing orange and red. When tested he proved to have a moderate weakness in both blue and yellow, but not in red or green. Violet, purple and blue he called uniformly purple. A seventh subject knew of no colour difficulty but when shown a demonstration spectrum she called the blue part " green " and the violet part " grey ". She proved to be very weak in blue and slightly weak in yellow, and to have the violet end of the spectrum very much darkened.

A woman was unable to distinguish yellow and white tiddlywinks, even after having the difference carefully pointed out to her. She did not have difficulty with any other colours than yellow. A very common form of colour weakness is often revealed when a person insists that certain greenish-blues, often called Eau de Nil, electric blue, or Cambridge blue, are really green and not blue. This is in my experience an indication of blue-yellow and not of red-green weakness.

We cannot be sure that a person is colour weak or colour blind unless strictly scientific tests have been applied. The opinions of friends and relatives are always interesting and may be very valuable, but must be taken in conjunction with the results of efficient tests. In one family where three sisters all proved to be red-green defectives with small yellow-blue weaknesses in addition, and in which the father and maternal grandfather were known to have been colour blind, the brother was suspected of being abnormal, because he had, in their opinion, " an unusual scale of colours ". In scientific tests, however, it was found that the sisters were all defective and that the brother was quite normal.

TERMINOLOGY OF COLOUR VISION DEFECTS

Red-green blindness is the commonest form of major colour vision defect and it is to this that the expression colour blindness is most generally applicable. There is a small number of persons with total colour blindness, who see only greys, black and white, and also a small number of people with such a marked weakness in yellow and/ or blue that they could be called yellow-blue blind. Objections have been raised to the expression colour blindness on two grounds : first, blindness is a dangerous word in any context, and is certainly

to be avoided when speaking to the patient or subject of a test. It is better to use any circumlocution than to say to his face that a person has a defect which can be called blindness, even though colour blindness has absolutely no relation to real blindness. Second, the expression colour blindness is false, because the majority of the colour blind have very good colour vision of their own kind, and they know it and can say so with appropriate indignation. In spite of these objections the expression colour blindness has been generally accepted and, for technical discussions, when we are not actually face to face with a patient, we might as well fall into line with the general usage.

Alternatives to the expression colour blindness have been suggested : the most popular are " deviant " and " anomalous " colour vision. These however, for technical purposes are thoroughly unsatisfactory, because the terms anomalous and deviant must be reserved for special defects. If not so reserved, other terms would have to be substituted, and that again would create further trouble. The difficulty over yellow and blue weaknesses is much less acute, because extreme forms of these defects are very rare. Perhaps the best terminology would be the use of the expressions red-green defective and yellow-blue defective, but not even these would escape criticism, and, on the whole it may be better to use the expression colour blindness in spite of its difficulties.

The most popular names for different classes of colour vision defectives were established on the assumption of the truth of the Young-Helmholtz or three-colour theory, which will be explained below. The red-green blind who confused red with dark brown or black were called protanopes, on the assumption that for them the first primary, red sensitivity, was missing. The red-green defectives who confused green and fawn or red without having either green or red extremely darkened, were called deuteranopes, on the assumption that in them the second primary, green sensitivity, was absent. Since there was, on this theory, only one other primary which could be lacking, all the defectives who had weaknesses in blue and/or yellow were called tritanopes, which meant that they lacked the third kind of primary, blue sensitivity.

This terminology was manifestly unsatisfactory, because both protanopes and deuteranopes confused reds and greens, and in deuteranopes the green which was supposed to be lacking was not replaced by darkness, so that they had no tendency to confuse green with dark grey or black. Rivers[16] proposed the Greek terms scotery-throus, which means " darkened-red ", for the protanopes, and photerythrous, which might be interpreted as " not-darkened-red ",

for the deuteranopes. These rather difficult words have not met with general acceptance. The term tritanope is just as unsatisfactory as protanope and deuteranope, because it is not at all clear how absence of the blue primary sensitivity can make a man insensitive to yellow while blue is unaffected. Yet this form of weakness is commoner than the form in which blue is more affected than yellow. The term tritanope, however, has been so obviously unsatisfactory that it has had little general use, and it may be overlooked : we can simply speak of blue-yellow or of blue and of yellow defectives without upsetting the technical parlance.

It has been claimed that there is a condition to be called yellow-blue blindness, which is extremely rare, but is parallel in nature to red-green blindness. Red and green can be distinguished, but yellow and blue are confused and matched with grey. Gates[64] mentions this, and says that the condition is a sex-linked recessive, like red-green blindness. In a later chapter an example of this very marked yellow-blue defect will be described, but all the evidence available here suggests that such cases are the extreme end-points of continuously distributed variations, and are not sex-linked.

The classification of individual differences in colour vision to be used in this book, with corresponding terminology, cannot be explained in detail and justified in this *Introduction*, because it was adopted as a result of the researches to be described, but the reader may be helped if it is given in a simple form at this stage, so that it can be seen at a glance and referred to when necessary. This classification is as follows, and may be compared with that given by the Colour Group.[67]

I. *Total Colour Blindness.* A rare, partially sex-linked Mendelian recessive.

II. *Acquired Colour Blindness.*[17] A variety of defects, resulting from nicotine or other drugs, from accidents and psychological causes generally of the hysterical type, and from diseases; possibly based on hereditary weaknesses in some cases.

III. *Red-Green Major Defects.* Totally sex-linked Mendelian recessive characters found in about 7 per cent. of men, of which there are six forms:—

A. *Protanopia.* Red-green blindness with darkened red (scoterythrous), generally extreme, sometimes moderate, genetic symbol : p.

B. *Red-Anomalous* colour vision. Not colour blindness in the sense of confusing red and green, but " red-different ". In two forms :—

(a) With red darkened, genetic symbol : r;

(b) With red of normal brightness, genetic symbol : r'.

C. *Deuteranopia.* Red-green blindness with red of normal brightness (photerythrous), generally moderate, but sometimes extreme. In two forms :—

(a) *Ordinary Deuteranopia*, red and green equally affected, genetic symbol : *d*.

(b) *Deviant* or *Anomalous Deuteranopia*, green very much more defective than red, genetic symbol : *d'*.

D. *Green-Anomalous* colour vision. Not colour blindness in the sense of confusing red and green, but " green-different", genetic symbol : *g*.

IV. *Red-Green Minor Defects.* Small variations, not sex-linked, continuous with the normal condition in distribution, taking two forms :—

(a) Red or Green " Deviant " colour vision, due to relatively reduced red or green sensitivity.

(b) Red-green " Colour Weakness", due to increased double differential threshold for red and green.

V. *Yellow-Blue Defects.* Always " minor " because there are no defects in yellow and/or blue strictly corresponding to the sex-linked major defects in red and green. Small variations, not sex-linked, continuous with the normal condition in distribution, taking two forms :—

(a) Yellow or Blue " Deviant " colour vision, due to relatively reduced yellow or blue sensitivity.

(b) Yellow-Blue " Colour Weakness ", due to increased double differential threshold for yellow and blue. Sometimes these weaknesses are almost great enough to justify the term " yellow-blue blindness ". Found in two forms :— (1) With and (2) Without Darkened Violet.

VI. *Exaggerated Fatiguability.* This may be a separate form of defect, independent or combined with any other weakness, and might be totally sex-linked. If definitely established as a sex-linked defect, the genetic symbol *f* might be suggested. It is not, as Girttmann thought,[5,30] a general characteristic of the anomalous.

Colour Vision in the Animal Kingdom

Numerous experiments[18] have been carried out to discover how far various animals are able to discriminate colours. Many of these experiments are marred or open to doubt because of the failure of the experimenters to realise the importance of matching the colours for brightness for the animals in question before it is assumed that they have been discriminated by hue alone. The possibility that colours discriminated by animals in some experiments might be identical in hue and brightness, but different in saturation, is a further important consideration which has not been taken into sufficient account. For example, a simple experiment carried out by

a student of mine will illustrate these points. A cat was taught by repeated trials to choose a red signal light as leading to a food box and to avoid a green light. The alternative food boxes and lights were interchanged in position irregularly to counteract the possibility of the animal forming habits to take the right or left path, or to approach the food box which had some peculiarity observed by it and not noticed by the experimenter, and the result seemed at first sight to be beyond dispute. It was soon realised, however, that the green light transmitted a far wider band of light rays than the red, and included rays which at least for human beings are much brighter. This difference for human vision was also probably present for the cat, which was simply learning to take the less brightly lighted path when it went to the food boxes. Even if we had first taken the precaution of varying the relative intensities of the lamps systematically, until it was certain that brightness differences had also been eliminated by random distribution, and the cat had still learned to take the red path, yet it would not have been proved that the cat could distinguish red and green by hue alone. Such an experiment could be done with a considerable proportion of extreme deuteranopes, who are unable to distinguish the hues of red and green of equal brightness, but some of whom can still distinguish them by saturation : the red is more saturated than the green, though both look purely yellow. In order to eliminate the influence of both saturation and brightness differences for an animal like a cat, whose colour vision, if any, and indeed, whose vision, if it does not see colours, may be considerably different from our own, it would require a very elaborate research. In many experiments on animal colour vision coloured papers and lights have been employed, and no attempt has been made to secure equality of brightness and saturation before apparent evidence of hue discrimination has been accepted.

Fox[19] has summarised experiments on bees which seem to prove beyond doubt that these insects can distinguish blue as a colour, but not red, which is completely confused with grey of equal darkness. They are, in addition, able to see by rays from the ultra-violet region of the spectrum, which are completely dark to us. Whether this ultra-violet light is a hue of definite quality, and if so, whether it is something like our violet, we cannot tell.

According to Walls's excellent account, unequivocal evidence for colour vision has been found for the Teleost fishes, and, in two such fish, Phoxinus laevis and Betta splendens, there was evidence that colour mixtures, such as yellow and blue or red and blue-green were complementary because they formed satisfactory matches for grey.

For frogs and toads, on the other hand, and for all reptiles except turtles and lizards, there appears to be no adequate evidence of colour vision. Among birds colour vision appears to be widespread, with the exception of owls, which are able to distinguish only brightness differences. The domestic fowl has trichromatic vision similar to our own, though it was for long thought to be blue and violet blind. For mammals no decisive evidence for colour vision has been found except among the Primates. There is no evidence that red is any different for the bull from grey of equal brightness. The great majority of mammals are either nocturnal or of twilight feeding habits, and colour vision would be of little biological advantage to them, though the loss of colour vision in this group could not be interpreted as an adaptation to a nocturnal life. It is an example of the disappearance of a useless function. The chimpanzee, New Guinea baboon, pig-tailed macaque, rhesus monkey, sooty mangabey, squirrel and spider monkeys have all been studied and found to have colour vision similar to that of man. The Lemuroids, however, have yielded negative results, and this, again, may be related to their nocturnal habits. It is interesting that the Cebus monkey appears to have colour vision like that of a human protanope, that is to say, it distinguishes yellow and blues, but confuses reds, yellows and greens of equal brightness and has great darkening of the red end of the spectrum.

Walls gives an interesting diagram of the possible phylogeny of colour vision in vertebrate animals. Colour vision may have started among primitive fish and passed from them to the bony fish or Teleosts on the one hand, and to reptiles on the other, among which it remains to-day only in the extreme branches, namely lizards and turtles. From early reptiles it was handed on to birds. From more primitive reptilian ancestors it was handed on to the mammalian stock, but has disappeared in all modern mammals except the Primates. Among those animals which have colour vision we often find bright colours on their bodies, which may serve for concealment, as in many fish and insects; for sexual display, as in many birds and insects and in those Primates which have brightly coloured sexual parts, and so on. Those animals which do not have colour vision are often grey, fawn, brownish, black or white, and do not have any brightly coloured parts or organs. The human body, however, is black, brown, yellowish or white, and yet man has good colour vision. Probably it was retained on account of its service in food seeking, especially in fruit eating habits. In personal adornment it has been exploited afresh for sexual display, aggression and in numerous activities in the cultural rather than the physiological heritage.

It is not necessary for an animal to have colour vision in order that it should be able to adapt its colouring to its environment. In the frog colour changes appropriate to the environment result from the varying interplay of three sets of pigment cells or chromatophores in the skin. One of these sets consists of unchanging opaque white cells; one of black, which is pale brown when thinly spread and black when dense; and one of orange or yellow. In pale colour effects the black pigment cells contract and the result is produced by combinations of white and yellow. Dark effects are produced by variable additions of the black pigment. Green is produced by a combination of filtering and reflection effects depending on these pigments. All skin colour changes are produced by light acting on the retina and on the skin itself, and are mediated by the nervous system and by hormones released by the pituitary gland.[20] Frogs and toads have never been shown to have colour vision.

POSSIBLE EVOLUTION OF HUMAN COLOUR VISION

The possible evolution of colour vision in the human race has been discussed by many writers, and clear accounts of the problem have been given by Parsons[21] and Myers.[22] Both Edridge-Green[23] and Ladd-Franklin,[24] in theories of colour vision to be discussed later, have claimed that human colour vision has evolved through stages represented by the forms of colour vision defect found to-day. Gladstone[25] showed that philological evidence based on the study of Homer indicated that the Ancient Greeks might have been deficient in colour vision, especially for blue and green. Geiger[26] and Magnus have also brought forward literary evidence of a most interesting kind to the same effect in respect of other early writings. Rivers,[27,28,29] using the Holmgren Wools Test and Lovibond's Tintometer, showed that there was a widespread tendency among primitive peoples to weakness in sensitivity to blue, and suggested that this was reflected in the frequent confusions of blue with green and the use of the same name for these colours. The explanation might be due to a lack of blue objects in the environments of these peoples, to a lack of interest in blue, to peculiarities of language itself, or to lack of colour sensitivity. Myers's discussion of the whole subject is extremely illuminating.[22]

There is a considerable amount of evidence that red-green blindness is decidedly less common among peoples of West African, American Indian and other groups, such as Papuans and Fijians, than among people of Caucasian stock. The following list, in Table 4,

TABLE 4

FREQUENCIES OF RED-GREEN MAJOR DEFECTIVES IN VARIOUS POPULATIONS
Additional Data are given by Gates[64]

Group	Investigator	Number tested	Red-Green Blind %
German Boys	von Planta[30]	2,000	7·95
American Whites	Miles[30]	1,286	8·40
do.	Haupt	448	7·81
Norwegian Girls	Waaler[31]	9,072	0·51
Norwegian Boys	Waaler[31]	9,049	8·01
British Men	Vernon and Straker[32]	6,000	7·49
British Men	Grieve[33]	16,180	6·63
Scottish Women	Pickford[34]	501	0·65
Scottish Men	Pickford[34]	464	7·80
Scottish Boys	Brown	525	7·43
Scottish Girls	Brown	252	0·46
Scottish Boys	Collins[30]	360	7·50
Scottish Men	Gray[35]	138	7·24
Spanish Whites	Lorenzo and McClure[30]	—	9·00
New Zealand Whites	Geddes[36]	2,000	6·00
Jewish Men	Garth	200	4·00
Indians	Geddes[36]	148	8·10
Todas (Wools Test)	Rivers[29]	503	8·56
Todas (Ishihara)	Clements[37]	320	12·80
Turkish Men	Garth[30]	—	5·30
Men of Upper Egypt (Wools Test)	Rivers and Randall-MacIver[28]	80	5·00
American Indians	Clements[37]	624	1·92
American Indians	Clements[37]	392	2·00
American Negroes	Clements[37]	325	3·71
American Negroes	Crooks[64]	2,019	3·91
Fijians	Geddes[36]	608	0·80
Bechuana Men	Squires[64]	417	3·40
Chinese Men	Kilborn and Beh[30]	1,115	6·30
Chinese Boys	Hsaio[30]	—	5·57

collected from various sources, shows this evidence. Those tested by Rivers would have shown a higher percentage of red-green blind subjects if the Ishihara Test had been used rather than Holmgren's wools, probably half as many again, and Clements[37] actually gives 12.8% in comparison with the 8.56% given by Rivers for Todas.

All the evidence shows that red-green blindness is found among males of Caucasian stock in the proportion of about 7 or 8%, whereas among the Todas studied by Rivers it was much more common, and in the American Indian, Negro and Fijian groups much less frequent.

Rivers found no red-green blind subjects in a group of Papuans, but, if the Ishihara Test were used, as many might be found among the Papuans as among the American Indians and Fijians. This suggests the possibility that the small percentages of red-green blind found in certain races with the Ishihara Test might correspond to the frequency of green anomalous subjects among whites (to be explained in a later chapter), because these subjects fail on the Ishihara but pass the Wools Test. Similarly, the moderate percentages found among Jews, Turks, Indians and Chinese would correspond to the frequencies of protanopes and deuteranopes among Europeans (excluding Jews). Thus the most prominent racial differences might be due to the variations in the distribution of types of defect, each of which, as will be shown later, is caused by a specific gene. It is most unlikely that these types of red-green defect represent stages in the evolution of human colour vision, the main characteristics of which were probably established long before man came on the scenes, but are due to a variety of defective mutations.

Other points about racial differences in colour vision will be dealt with in later chapters, though it may be said here that there is no convincing evidence that colour vision passed through phases which might correspond to the hypothetical stages of Edridge-Green's or Ladd-Franklin's colour theories.

COLOUR VISION OF CHILDREN* [68]

At Rivers's suggestion Tucker[38] measured the thresholds for blue in English children, using Lovibond's Tintometer. She found thresholds as high as Rivers found for Egyptians, and claimed that there was an increase in threshold from older to younger children. This supported the view that there might have been an evolution in human colour vision by indicating that children of more advanced groups tended to recapitulate the steps in their development. Mc-Dougall,[39] Myers [40] and Valentine,[41] however, took the view that the development of colour vision in children is completed at an early age. They used the attractiveness of colours for children as the basis of their tests, whereas Winch[42,43] and Garbini have considered that attractiveness might merely indicate brightness differences (which Valentine doubts), and used a matching method. Similar work has been done by Holden and Bosse[44] and by Neumann. In all tests in which matching is used it is impossible to avoid also testing the process of comparison itself, which may develop later than

*I am indebted to Mr. Robert Brown for compiling the data in this Section.

colour sensation, and in naming-tests the use of language is involved, and this, especially for children, may be influenced by home environment to an unknown extent. Even among adults this is a serious matter, and, as Myers has pointed out, the Welsh have no name for blue.[22] Nevertheless, these experiments on children support the philological evidence for the development of colour vision, as indicated in Table 5. The results of Valentine on a two months' infant were gained by timing fixations, while those on the same child at seven months were obtained by a " grasping " test.

TABLE 5

ORDER OF PREFERENCE AND " PERCEPTION " OF COLOURS BY CHILDREN COMPARED WITH PHILOLOGICAL EVIDENCE OF COLOUR SENSE DEVELOPMENT

Source of Data		Order of Preference or Correct " Perception "
Philological Research		White, Black, Red, Yellow, Green, Blue.
Work on Children	Valentine	Yellow, White, Pink, Red, Brown, Black, Green, Blue, Violet (3 months).
		Yellow, Red, Pink, Grey, Violet, White, Green, Black, Blue (7 months).
	Garbini	White, Black, Red, Green, Yellow, Blue.
	Winch	Black, White, Red, Blue, Green, Yellow, Violet, Orange.
	Neumann	Black, White, Red, Blue, Green, Yellow, Violet, Orange.
	Holden and Bosse	Black, White, Red, Orange, Yellow (8 months), with Green, Blue, Violet (10-12 months).
	Staples	Red, Yellow, Blue, Green (15 months).

Staples[45] investigated the responses of infants to colour by a " grasping " test, and by recording the time they looked at the colour seen against a grey background. She reports that colour is experienced by children as early as the end of the third month, but without differentiation of hue. By fifteen months red, yellow, blue and green are differentiated, and their effectiveness as stimuli is in that order. Before two years of age infants can fully discern these colours, and girls are slightly more mature in this respect than boys. Chase[46] reports that colour discrimination is present in infants as early as fifteen days, and is of the opinion that all infants have sensations of colour as early as three months and can distinguish different colours when five or six months old.

It is not certain that in these researches the relative brightness and effectiveness of different colours as stimuli have not influenced the results just as in many experiments on animals. This criticism

is supported by the findings of Smith,[47] who showed, in an investigation of the effectiveness of various colours for use as road signs, that their order was red, orange, yellow, green, blue; while blue showed least visibility for all trained observers with normal colour vision. It seemed therefore essential that an investigation of the colour vision of children should be carried out in which brightness differences were satisfactorily equalised, and this will be reported in a later Chapter.

THEORIES OF COLOUR VISION

Science generally develops by three steps : first the observation of crude or unsystematised data; second the formulation of hypotheses to account for these data; third the use of systematically planned observations and experiments to test the hypotheses, which must then be accepted, modified for further tests or rejected accordingly. A simple account will be given of the four principal theories of colour vision. These four theories, due to Hering, Young, Ladd-Franklin and Edridge-Green, were all put forward before 1900, in their original forms. Granit's conception of dominators and modulators, and Hartridge's data supporting a multi-colour theory, however, will be explained and discussed in the final chapter. It is better to start with the four theories which form the traditional background for the study of colour vision. Polyak's discussion of the two main theories should be consulted.[63]

THE FOUR-COLOUR THEORY

The idea that there might be four primaries, red, yellow, green and blue, and that intermediate hues are not separate sensations, was formulated as a serious theory of colour vision by Hering[48,49] in the latter part of the nineteenth century. Considering the facts of colour mixing, the colour circle, complementary colours, after-sensations and simultaneous contrast, he took the view that these primaries could be arranged in two pairs, red-green and yellow-blue, and he added black-white as a third and hueless pair. He supposed that physiological processes of opposite nature might excite sensations of opposite quality according to these pairs. When there was no stimulation the opposed processes would balance in the middle and there would be no sensations of hue, but the intermediate deep grey which is experienced when the eye is at rest in complete darkness he called the " self-light " of the retina and attributed it to the balanced processes of the system. White, red and yellow he regarded as produced by destructive or katabolic processes, and their opposites

black, green and blue as due to constructive or anabolic processes. When monochromatic red or yellow light falls upon the retina katabolic processes are set up and the corresponding colour is experienced in saturation proportional to the intensity of stimulation. Monochromatic green or blue light has an opposite effect, producing anabolic processes. Similarly, white light produces katabolism and absence of light stimulation produces anabolism in the white-black system. Intermediate light rays, like orange, if monochromatic, affect both their neighbouring systems, in proportion to their nearness to the primaries concerned. Polychromatic colours affect all the systems involved. Hering found it necessary to assume in addition that all the rays in the spectrum have a certain effect on the white side of the white-black system, so that all colours have whiteness added to them, and further, he assumed that red and yellow have inherent brightness on their own account and green and blue inherent darkness, thus explaining the warmth of the first two and the coldness of the second two. Since pure green and red are not complementary, it seemed necessary to assume that the red primary was not spectrum red but carmine, which is a psychologically pure and physiologically stable red, though physically compound.

This theory will be discussed more critically later, but it accounts extremely well for the general phenomena of colour vision : the colour circle, complementary colours, brightness and saturation, black and white, and especially well for negative after sensations, which would appear to be due to the tendency of the disturbed colour system to swing back to its balanced position. To account for simultaneous contrast the assumption is required that the opposite effect is produced in neighbouring regions of the retina by a given stimulation of one area. Even the familiar red-green and yellow-blue colour vision defects seemed easy to explain as due to the absence of the corresponding systems, so that there was an inadequate differential response to the light waves in question. The darkening of the red in protanopes he assumed to be due to pigment in the retina and optical system, but this is not satisfactory.

When Hering put forward his theory it was not known how complex and variable colour vision defects would prove to be on fuller investigation, and the mere absence of the red-green system seemed sufficient to account for red-green blindness. Houstoun, after a most interesting series of researches, has suggested some useful amendments of the theory.[50] His most important suggestion is to think of Hering's light-sensitive substances as being replaced by the capacity of the cones, or light-sensitive cells of the retina, to respond

to stimulation with two alternative frequencies of electrical discharge, and that there should be two sets of such cones with different pairs of frequencies. One set will give rise to red and green sensations; the other to yellow and blue. The first frequency of discharge of cones in the red-green system will correspond to red and the alternative frequency to green, and similarly for the yellow and blue system. Since he thinks responses to light and darkness must be controlled by a system independent of colour to some extent, it is to be assumed that he would add a third system of cones with one frequency for white and another for black. It would be useless to think of the white and black sensations as determined in daylight vision by the rods, because they are totally out of action except in extremely dim twilight, when they give colourless sensations. Thus Houstoun's theory would lead us to expect cones to be in sets of three.

Houstoun has to suppose that in each of the three systems there are cells which have the potentiality of two distinct rates of electrical discharge, corresponding to complementary colours and to black and white, accordingly, and that there is a sharply defined point of change over from one discharge rate to the other. If this hypothesis can be sustained the laws of colour mixing will be satisfied. Red rays set off a certain rate of discharge in the red-green cones; as we approach orange the yellow-blue cones come into action; yellow affects only yellow-blue cones, but yellow-green will affect the yellow cones in the same way as yellow and the red-green cones in their alternative way to red, and so on. Polychromatic colours will affect all the systems to an appropriate extent, just as in the original Hering theory. Houstoun is not explicit about white, grey and black, but the brightness level of colours and their mixtures is not dependent on variations of hue and saturation sensitivity alone, and in order to explain this it will be necessary to assume a third system, as suggested above. The self-light of the retina might be accounted for by a very small number of discharges occurring spontaneously in all systems, since all primaries, combined in very small quantities, would produce a grey of very low intensity.

Houstoun's theory of periodic electrical discharge completely overcomes the objection raised against Hering's four-colour theory by Ladd-Franklin and many other critics, that a positive sensation cannot be supposed to arise from an anabolic or assimilative chemical change.

In Houstoun's scheme it may be difficult to accept the possibility that a single sensitive cell can have two sharply different modes of

electrical discharge which differentiate complementary colours. An interesting adaptation of the theory would therefore be to suppose that the alternative rates of discharge were attributes of different cells. We could put forward the hypothesis of two pairs of hue responding cells : in the red-green pair one cell responds to red, the other to green; in the yellow-blue pair one responds to yellow and the other to blue. The saturation will depend on the number of cells excited. The white responding cell may respond only to white and make no discharge for black, which could be a purely contrast effect. This theory, again, would lead us to expect the cones to be in sets of three, there being two different kinds of sets : red, green and white; and yellow, blue and white.

If a part of the retina is stimulated with red rays alone, a saturated red may be produced, which, like spectrum red, is slightly orange in hue because the red-responding cells will all be active and a very small number of the yellow-responding cells will be active too. As we add the green rays to displace the red ones gradually, fewer and fewer of the red-responding cells will react and more and more of the green-responding ones. At a central point equal numbers of both will react, and at this point a very desaturated yellow will be produced. At the other extreme, the red-responding and yellow-responding cells will cease to react and we shall be left with a green to which no yellow is added. For a person with normal red-green vision the points of change from red to yellow and from yellow to green will be definite and will leave a very narrow margin within which desaturated yellow may be matched by the red-green mixture. Any tendency of the red-responding cells to react with more than minimal readiness to green rays, and *vice versa*, will result in the widening of this margin. If the cells fail to differentiate red and green in their responses, yellow will be matched throughout by the mixture, whatever the proportions of red to green. At the green end, however, there will be a more colour-less and at the red end a more yellowish sensation, because spectrum red overlaps the region of yellow responses more than spectrum green. If we start with spectrum yellow and blue, essentially the same principles apply, with the difference that the mixture of equal proportions will match a neutral grey, because the hues with which we started are complementary. The weaker the capacity of the yellow and blue-responding cells to differentiate yellow and blue, the wider margin of the mixture will accurately match a grey of equal brightness, until at an extreme point both yellow and blue and all mixtures of them would be identical with grey. At the same time, in either the red-green or the yellow-blue system, any tendency for the main

change to be displaced from the normal central position in the red, green, yellow or blue directions, would result in a deviation from the normal mixture of red and green which matched yellow or of the normal mixture of yellow and blue which matched grey. In hypothesis both types of modification in the differentiating systems are possible, and we could have any combination of these four different variations from normality. At the same time, any of the four types of responding cells might be reduced in numbers or put out of action. With these possibilities it will be found that all types of red-green and yellow-blue colour vision defect can be accounted for with far more efficiency than on any other theory of colour vision. Motokawa's recent work points strongly in the same direction.[65]

THE THREE-COLOUR THEORY

Thomas Young put forward in 1801 a theory which required only three primaries, red, yellow and blue, in accordance with the experience of artists in colour mixing. It is easy to make green by means of blue and yellow in the artist's way, as explained in a previous paragraph, but the artist would not be able to make yellow satisfactorily by mixing red and green : the effect is " muddy " and desaturated. From the point of view of a three-colour theory, however, red, green and blue are more satisfactory, because with monochromatic yellow and blue one cannot make green, but with monochromatic red, green and blue one can match all colours in hue, though not in saturation. Young soon altered his theory to employ red, green and blue, and these were the primaries chosen by Helmholtz when he elaborated the theory known by their joint names later in the century.[51]

In the Young-Helmholtz theory one set of cones will function in response to rays at the red end of the spectrum, one set in response to rays from the middle or green part, and a third set in response to rays from the blue and violet end. There will be considerable overlapping which, according to Walls, must be so great that all cones respond almost to the whole spectrum, but the sum of their responses will be mainly weighted with red at one end, green in the middle and blue at the other end. Wright's data do not support the view that the overlapping is as great as this.[62] Nevertheless, it might account for the brightness of yellow-greens and for the fact that spectrum yellows are of relatively low saturation. Black results from the absence of stimulation, and greys result from all three in complementary proportions but low intensities, while white occurs

when all are stimulated with great intensity. Colour sensations result from a preponderance of one type of response over the other two, or of two over the third.

It would be more satisfactory to take as primaries three colours each of which is psychologically unanalysable, but we need a slightly orange red, a slightly yellowish green and a violet blue. These three divide the colour circle efficiently into three sections such that any two taken together are complementary to the third. Such primaries are well represented by the famous sets of tricolour gelatine filters used for colour photography. Such filters are, however, very far from being monochromatic, and include between them all possible intermediates, while the green and blue usually transmit some red light. Colour mixing experiments which can be done with these filters are therefore very poor evidence for the Young-Helmholtz theory. The intermediates—especially yellow, which is an inter-mediate on this theory—are already present in the polychromatic primaries. To prove the Young-Helmholtz theory monochromatic primaries must be used.

On this theory complementary after-sensations are attributed to fatigue of the receptors, which take a certain time to recover from stimulation and the colour corresponding to which is therefore subtracted from grey or white. Simultaneous contrast effects are attributed to inference or to the tendency to excitation of complemen-tary effects in neighbouring areas of the retina. The theory would lead us to expect three main types of colour vision defect : red-blindness, green-blindness and blue-blindness. The varieties of colour vision defect are too complex for such a simple explanation. Since yellow is produced by the combined stimulation of red and green receptors, it would be exceedingly difficult to account for the colour vision of a person who could not distinguish yellow from white tiddlywinks, but had no weakness in red, green or blue. At the same time, many persons are found who cannot distinguish red from green by any effort, but who have no difficulty whatever with yellow. Nevertheless, the Young-Helmholtz theory has been of great importance in the history of colour vision, and has been and still is accepted almost as a dogma in many circles.

LADD-FRANKLIN'S THEORY[52]

Ladd-Franklin's theory of colour vision was a compromise between the three- and four-colour theories. She expressed the view that in the beginning of the evolution of colour vision there was sensitivity

to light alone, without discrimination of colour. This would correspond to the sensitivity of the majority of mammals, which are totally colour blind, and to that of the totally colour blind met with rarely among human beings. Colour vision, however, appears to have started at least as low as the bony fishes, among vertebrates, and is found in insects too. Hence those higher animals which lack it, and also the various kinds of colour blindness in human beings, cannot be viewed as intermediate stages towards its evolution, but must be regressive, and may or may not reflect its original steps as clearly as Ladd-Franklin thought. She took the view, however, that as evolution proceeded a substance sensitive to light became subdivided, forming two subsidiary substances, one of which was sensitive to the long and the other to the short waves in the visible spectrum. The long wave sensitivity gave yellow and the short gave blue vision, but mixed light still affected both substances together as before, and gave white. A second step in evolution divided the yellow substance in the same way into two parts, giving different sensations for red and green and a combined sensation for yellow as before. Thus the yellow vision of the red-green blind could be explained by saying that they had arrested development at the second stage, and the totally colour blind could be considered to have arrested development at the first stage. In this connection it is interesting that totally colour blind human subjects usually have very poor light adaptation—photophobia—and their vision may be confined to the functions of the rods. The study of some completely nocturnal animals, like the bat, shows that they have lost their cones, while study of others which are less completely nocturnal, like the rat, shows that the number of remaining cones is very small indeed. On the other hand, lack of colour vision is not in general coupled with absence of cones. Hence there might be two stages of colourless vision, one which is nocturnal and corresponds to rod-functioning alone, and the other which is diurnal and corresponds to colourless cone vision.

Although Ladd-Franklin's theory combines some of the advantages of both the three- and the four-colour theories, it is liable to the principal objections to the three-colour theory without gaining the most important advantages of the theory of four primaries. Thus, three-colour mixing experiments with monochromatic colours will not support the Ladd-Franklin theory if they do not also support the Young-Helmholtz theory. Every weakness in yellow must, on Ladd-Franklin's theory, imply a corresponding weakness in red and/or green, which is not borne out by fact. The two types of red-green blind cannot be satisfactorily explained on her theory,

and there are several other kinds of colour defect which would be even more difficult to explain, just as they are on the Young-Helmholtz theory. These will be dealt with fully later.

EDRIDGE-GREEN'S THEORY[53]

This theory, put forward in 1891, was completely different. Edridge-Green supposes that the discrimination of colours is like the discrimination of the differences between the lengths of poles, the sizes of boxes or the lengths between the crests of waves on the sea. It is, in fact, a discrimination of the differences between electro-magnetic waves by wave-length, but, instead of seeing long, medium and short waves, for example, we see red, green and violet. The more efficient our psycho-physical functions in discriminating wave-lengths the better colour vision we have. Edridge-Green assumed that the essential light sensitive substance of the retina was the visual purple, which is bleached by light and tends to accumulate in the dark when there is little or no stimulation. His theory, like that of Ladd-Franklin, was a theory of evolution which assumed that various degrees of colour sensitivity in man were stages of development. Thus the most primitive vision discriminates only between light and dark. The second stage discriminates hue as well, and has blue for short and yellow for long waves. In the third stage there is the ability to discriminate the middle rays of the spectrum as green, and the ends remain yellow (or perhaps red) and blue (or perhaps violet). The fourth stage brings the distinction of yellow from red and green, and has four hues, red, yellow, green and blue (or violet). In the fifth stage blue and violet are distinguished; in the sixth orange is distinguished from red and yellow. The seventh stage brings indigo and has all the familiar colours of the spectrum. More stages may yet evolve. Edridge-Green has called these the monochromic, dichromic, trichromic, tetrachromic, pentachromic, hexachromic and heptachromic stages respectively. His terms trichromic and dichromic must not be confused with the terms trichromatic and dichromatic which are used in the Young-Helmholtz theory. Trichromatic colour vision means colour vision in which all hues can be matched with three primaries; in dichromatic vision only two are required, as in those who are extremely red-green blind. Many if not all dichromatics are what Edridge-Green would call dichromic, in the sense that they see only two hues, yellow and blue; but a person with trichromatic colour vision might be a tri- tetra- penta- hexa- or heptachromic on Edridge-Green's theory. The monochromics

correspond to the totally colour blind; the dichromics are those with extreme red-green blindness; the trichromics are the incompletely red-green blind; the tetra- and pentachromics according to Edridge-Green's account, are people with common types of colour weakness, the pentachromics tending to confuse yellow and orange, and the tetrachromics to confuse blue and violet. The hexachromics are those with normal colour vision, but who cannot distinguish indigo; and the heptachromics are the most sensitive, to whom indigo is different from blue and violet. There are, of course, no sharp distinctions between these seven classes, which merge into each other continuously. The hexachromic is the commonest class, and on either side of it the remaining classes are arranged in order of decreasing frequency. To be able to distinguish indigo is unusual but not rare. To tend to confuse yellow and orange is commoner than the tendency to confuse blue and violet, and these in turn are commoner than the tendency to divide the spectrum into no more than three colours. The confusion of red, yellow and green is still rarer and total inability to distinguish colours from grey is very rare indeed.

On Edridge-Green's theory there are no primaries in the usual sense of the term : there are simply different degrees of ability for colour discrimination, and there are as many primary capacities for a given person as the number of distinct hues he can see—purples, magenta and carmine, of course, being treated as mixtures. In the same way there are no " primaries " in the sensations of tone in hearing, but simply a multiplicity of differences.

Certain objections to this theory should be carried in mind. One is the difficulty of thinking of the discrimination of light waves by hue as being of the same general nature as the discrimination of sizes, weights, heights, temperatures and so on, but this would not be an overwhelming objection to the theory if it was otherwise sound. It may be said that sensations of warmth and coolness are indications in consciousness of the molecular vibration-rates in the bodies we touch. This is not less difficult to understand than the suggestion that hues are conscious indications of differences in wave lengths of the light rays which stimulate the eye. It is a more serious objection that these seven classes do not represent accurately the true state of affairs in the distribution of colour defects. The classification of colour-vision differences calls for a much more complex system than that of Edridge-Green. It is difficult to avoid the impression that he has tried to force the differences he observed into a ready-made scheme. His observations of colour-vision

difference were endangered by his reliance on the use of the spec-
trometer as the essential instrument, and by too great insistence on
the value of the subject's use of colour names. A profounder know-
ledge of psycho-physical research would probably have led him to
replace his spectrometer-naming technique with a more efficient
method. Nevertheless, his clinical descriptions of various forms of
colour-vision defects are of quite exceptional interest and deserve
the thorough attention of all students of the subject, even though
half-a-century has elapsed since he made them first.

Binocular Colour Combinations

Much interest centres about the possibility that a good yellow
might be made from a binocular combination of red and green, one
colour presented to each eye. According to Walls, " There is no
color-sensation which can be produced by mixing two lights in one
eye, that cannot be duplicated by supplying two lights, independently,
one to each eye ".[54] He also puts forward an interesting hypothesis
that all colour syntheses, both binocular and monocular, take place
in a single locus, believed to be the lateral geniculate nucleus, whereas
fusion of binocular stereoscopic patterns may take place in the
laminae of the striate area of the visual cortex.[55]

In order to study binocular colour combinations, two colours,
one supplied to each eye, may be combined by means of a simple
stereoscope, fitted with a colour-filter holder to take the place of the
usual stereoscopic double picture. One colour will stimulate each
eye independently.

In experiments of this kind, carried out on eleven subjects with
normal colour vision, the eight Ilford monochromatic filters were
used, together with Ilford Micro No. 6, which is a suitable purple.
Similar experiments with abnormal subjects will be reported later.
The nine colours were combined binocularly in pairs, starting with
red on the left and taking each other colour in turn on the right.
Then orange was placed on the left and each other colour except
red was placed on the right, and so on, until purple and violet were
the only pair remaining to be combined. In order to compensate
for the possible effect of the dominant eye, whichever it was for each
subject, the experiment was then repeated with the side to side
positions reversed.

The degree of combination was estimated on a ten-point scale,
o being complete absence of combination and 1.0 being perfect
fusion. Five intermediate points were used : 0.1, 0.3, 0.5, 0.7 and

o.9, in order to simplify the experimental task and also because no colour pair completely failed to fuse or gave perfect combination. The estimates were entered in order in a 9 × 9 table, like a correlation table, and the diagonal cells were then filled with 1.o's, because they represent fusion of each colour with itself, which is always perfect.

The resulting table was then factor analysed by the simple summation method, and the following factor loadings were obtained from the experiment with one experienced observer who had normal colour vision. The results for the other ten observers were all of the same kind. Although the figures in the 9 × 9 table obtained in the

TABLE 6

FACTORIAL ANALYSIS OF BINOCULAR COLOUR COMBINATIONS

Colours combined	General factor	First bipolar	Second bipolar
Purple	·648	−·247	+·723
Red	·735	−·589	+·197
Orange	·765	−·580	−·076
Yellow	·867	−·402	−·349
Yellow-Green	·839	−·089	−·676
Green	·765	+·145	−·641
Blue-Green	·854	+·638	−·158
Blue	·706	+·551	+·399
Violet	·618	+·573	+·599

experiment were not correlations, it is legitimate to apply factorial analysis to them on the assumption that they were analogous with correlations, and I am greatly indebted to Professor Sir Godfrey H. Thomson for a very interesting discussion with him concerning this table of factor loadings.

The general factor shows that all colours have a strong combining tendency when presented independently one to each eye in pairs. The bipolar factors show that there are certain very significant limitations to the ways in which these combinations can be made. Both bipolars show that complementaries are very difficult to combine in binocular vision, and the second bipolar shows clearly that bright colours are difficult to combine with dark. Red and green can be combined to a certain extent, under the conditions described, but only with considerable difficulty, and little or no support for the Young-Helmholtz theory will be found in this experiment. It clearly supports a four-colour theory of the Hering or Houstoun type, in which opposite colours would be expected to combine by a " neutralising " process in the retina of one eye, but not when

presented separately to the two eyes, whereas neighbouring colours would be expected to combine readily in either way, which they do, as shown by ordinary laboratory experiments on colour mixing.

The fact that complementary colours are extremely difficult to combine when presented separately one to each eye, but very easy to combine in one eye alone, also throw doubt on the theory that all colour combinations take place in a single locus of the brain, and not in the retina. It is more likely that complementaries combine in the retina, though neighbouring colours may be combined in the lateral geniculate nucleus. Further experiments are in progress to see whether there are any characteristic differences between the various types of colour blind and anomalous subjects in their capacities for binocular colour combination.

THE RAYLEIGH EQUATION

The experiment now traditionally known as the Rayleigh equation was first described by Rayleigh in 1881[56] and consisted in mixing monochromatic red and green to match a monochromatic yellow. These colours were obtained by means of an apparatus with slits arranged to allow the appropriate parts of a spectrum to pass. The red and green rays were mixed and the yellow rays were brought into such a position that they could be compared with the mixture. Rayleigh described three methods of doing the experiment, two with spectrum colours and one with coloured disks combined by a rotating prism. The quantities of red and green could be adjusted to give a match with the yellow standard. Edridge-Green,[6] who carried out a series of tests with Rayleigh's second apparatus, assures us that an exact match is possible, for brightness, hue and saturation. In the form of the apparatus described by Nagel,[57] the relative widths of the red and green slits are varied inversely by the movement of a central block, so that the colour which is being added at the same time tends to become a wider band of rays and is therefore less strictly monochromatic, and *vice versa*. An apparatus of this type, whether Rayleigh's or Nagel's, or indeed any other kind of apparatus with the same function, is usually called an anomaloscope, for reasons which will be explained later.

Rayleigh found that the majority of subjects required almost the same proportions of red and green to match the yellow, but he was immensely fortunate, and, among twenty-three male observers, he found that his three brothers-in-law and two other men, one of whom was J. J. Thomson, required far more green than the majority, while

two more differed in the opposite direction. His fourth brother-in-law and his three sisters-in-law he found to be normal.

Subjects who differed as much from the normal as those seven first described by Rayleigh have become known as " anomalous trichromats ". On the assumption of the truth of the three-colour theory, the Rayleigh equation tested the relative strength of the red and green primaries. Blue was not tested. On the three-colour theory the completely red-green blind would be insensitive to one or other of the two primaries, red and green, and therefore not more than two primaries would be required by them to match all the hues which they see. Between the colour blind and the normal, who would, of course, be trichromats on this theory, a certain number of intermediates would be expected, according to the random variability which affects all human traits and characteristics. It was assumed by many people that the subjects who still required three primaries and yet differed from the normal in the two ways described by Rayleigh were these intermediates, and they were called anomalous trichromats accordingly, one type requiring more red and the other more green than the normal. These rather tempting assumptions have led to the most unfortunate confusions in the study of colour vision, for the so-called anomalous trichromats are not intermediates between the colour blind and the normal.

At the present time there are three ways in which the expression anomalous colour vision is used. The majority of workers, including Nagel,[57] who claimed to be anomalous himself, seem to use this expression to refer to all subjects who are weak in red-green vision, but who are not as weak as the extremely red-green blind. Edridge-Green,[6] however, has pointed out that many slightly colour weak subjects are willing to accept the normal Rayleigh Equation, though their most frequent choice may be different. They are not weak enough to be detected by ordinary tests for colour blindness. He found other subjects who are quite unable to accept the normal equation and invariably reject it. He wishes to call the first group colour weak and the second group anomalous in the strict sense. The third use of the term anomalous is that of ophthalmologists and colour-vision testers who do not wish to say that any person is colour blind. There are excellent reasons for avoiding the term blindness in any form, but it is unsatisfactory to use the term anomalous in this way in technical discussions, because it is required for the special condition first pointed out by Rayleigh. There is another and interesting way of thinking of anomalous colour vision. As Parsons has pointed out,[58] the colour blind are subject to a form of reduction of

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colour vision, in which fewer than the normal number of hues is discriminated. Hence a colour-blind person can make many matches in colour mixing experiments which would be rejected by the normal, but he always accepts any colour matches which a normal person makes. The anomalous are exceptions to Parson's rule. They reject the red and green mixture with which the normal person matches sodium yellow, and accept another mixture which the normal person rejects. They are almost as good at discriminating hue differences as the normal, but discriminate them in a different way.

There are excellent reasons for the difficulties about the term anomalous colour vision. Here it will be used strictly in Edridge-Green's sense, and applied to those subjects who reject the normal Rayleigh equation by a wide margin. This distinguishes them from the colour blind, who almost always accept the normal equation and can often accept the anomalous equations as well.

Rayleigh was exceptionally far-seeing and a careful consideration of his paper[56] will reveal the following points :—(1) He did not assume that the Rayleigh equation directly fell in line with and demonstrated the truth of the three-colour theory; (2) He doubted that all individual differences in colour vision were normally distributed; (3) He showed that the two kinds of anomalous colour vision differed in certain characteristic ways from colour blindness; (4) He threw doubt on the view that colour blindness could be divided into two classes, red blindness and green blindness ; (5) Nevertheless he showed the essential way in which protanopes differ from deuteranopes; (6) By observing three brothers who had the same green anomalous defect, while their fourth brother and three sisters were normal, he provided a piece of evidence indicating that the green anomalous defect is inherited as a distinct and definite character, while this small pedigree is now seen to correspond to the view that the green anomalous condition is inherited as a sex-linked Mendelian character.

ORIGIN OF THE PRESENT EXPERIMENTS

More than one form of anomaloscope exists, and Collins[30, 59] has shown that essentially the same experiment can be done with Hering's coloured papers. In this experiment a disk composed of red and green variable sectors is adjusted so that the ratio of red to green in the whole 360° matches a yellow which is desaturated and adjusted to the necessary brightness with variable sectors of black and white. Her disks were all mounted on the same rotator, the red-green disk being large and the yellow-black-white disk being

small, so that a direct comparison was possible. When I appealed to her to suggest a sensitive test of colour vision, she sent me the colour papers suitable to set up a similar experiment.

The results of the first tests with this apparatus were very surprising. In the preliminary experiments there were about five normal subjects, one who was green anomalous and two who were extreme deuteranopes. It was expected that the anomalous subject would give an equation intermediate in deviation from the normal, and the colour blind would give an equation of extreme deviation. Assuming the truth of the Young-Helmholtz theory at the time, it was thought that green anomalous subjects would be part way to " green blind " and red anomalous part way to " red blind ". Neither of these expectations was fulfilled, and the experiments were held up at this stage until an interesting point was noticed about certain readings which were jotted down on the blackboard while testing a husband and wife. The wife had laughed at her husband for making certain slight colour mistakes, as she thought, but the tests had shown at first that she had a greater weakness in green than he. Somewhat piqued, she had asked for a re-test, and this time she had exactly agreed with him. It seemed certain that the experiments were efficiently carried out, and, though Collins has shown that there are very slight variations in the red-green equation for a given subject from day to day, the differences were much too great to be accounted for in that way. It was then noticed that in the second test, in which the wife had agreed with her husband, she had accepted the yellow-black-white disk as he had left it, namely, with more black than in her first test. This fact gave the clue required, and the hypothesis was formulated that there might be a range of colour matches acceptable to each subject and depending on the proportions of black with which the yellow was mixed. If, for two subjects, these ranges were to overlap, then they might be able to accept the same red-green equation if the proportion of black was adjusted suitably, although their mean matching points were considerably different. The husband and wife, it appeared, had failed to agree when the white-black ratio was different, but had agreed when it was the same. So long as they were within the limits of overlap of their ranges they would agree, but outside these limits they would differ.

It was then decided to recall the subjects tested for a new series of tests in which each should be made to reveal the range of ratios within which he could accept the red-green mixture as a match for the standard yellow provided there was also a brightness match.

Still working on the assumption of the Young-Helmholtz theory, the hypothesis was now formulated that there would be found all degrees of red-weakness, shown by increasingly large ranges of matching towards red, the red anomalous being intermediates and the " red blind " the extremes, and similarly on the green side for the green anomalous and the " green blind ". It was assumed that the more a person's red-green equation differed from the normal the bigger range of matches he would make.

This third expectation based on the Young-Helmholtz theory was also unfulfilled. We tested a number of subjects with the greatest possible care, and were astonished to find that the green anomalous had a very big deviation to the green side but a small range, while the so-called " green blind " had a vast range of possible matches stretching as far into the red as into the green side of the red-green mixture, and therefore a very small average deviation. Subsequently the same was found to be true of the so-called " red blind ", while the red anomalous had a very big red deviation and a very small matching range. This result, of course, could have been predicted from the observations which Edridge-Green, and Rayleigh himself, had published half-a-century ago, if I had not been assuming the truth of the Young-Helmholtz theory. It was therefore apparent that the usual method of using the Rayleigh equation, in which the degree of deviation is supposed to be an adequate measure of colour weakness in the colour towards which the deviation occurs, was futile and based on a mistaken view of the nature of colour-vision defects. The Young-Helmholtz theory immediately became subject to the sharpest suspicion, because there was no correlation between deviation and range of colour matches. Breakdown of the expectations based on the theory was the precondition of new insight into colour vision.

It became apparent that there was uncharted ground to study, and a series of experiments was planned with the rotating disks. It seemed that other tests of the subject's ability to make colour matches under the conditions of the experiment and apart from the effects of red-green weaknesses would be valuable as a safeguard in assessing those weaknesses. We chose a blue paper which, when rotated on the colour wheel with the standard yellow of the Rayleigh Equation, would be almost grey. In order to make the conditions as near as possible to those of the Rayleigh Equation a blue was chosen which would produce a grey which required not simply black and white to match it, but in addition a very small sector of green. This green-black-white disk looked very faintly green when at its darkest, grey when of intermediate brightness and white when at its brightest

level. Although green was present, the disks looked grey when matched.

Again an assumption based on the Young-Helmholtz theory proved unsatisfactory, because it was thought that yellow and blue would almost never vary, except in the rare cases of " violet blindness ", and that this yellow-blue test could be used as a control for the Rayleigh Equation, so that we could be certain that those who had unusually wide ranges of matching in red and green were not simply incompetent or careless at the test itself. Surprisingly enough, both blue and yellow weak subjects of several kinds were soon found. Doubts about the Young-Helmholtz theory now became even greater and the problem of testing theories was added to that of testing individuals. A shortened account of the work, concentrating mainly on the Four-Colour Test, to be described in Chapter IX, has been published elsewhere.[60]

Important discussions of colour-vision defects have been published recently by Willmer[61] and Wright,[62] both of whom are prepared to support trichromatic theories, though in different forms, while Wright has pointed out some of the difficulties in using the Nagel Anomaloscope to distinguish the anomalous from the colour blind. The present book was largely complete in MS. about the time these two works were published. It deals with the whole subject from a different point of view, namely that of the investigation of individual differences by the methods generally accepted in experimental psychology.

THE ROTATING DISKS EXPERIMENT: NORMAL, DEVIANT AND COLOUR-WEAK SUBJECTS

THE purpose of this experiment was to study and measure accurately the individual differences found in colour sensitivity for red, green, yellow and blue. It was planned to measure the small differences between people with normal colour vision, together with any moderate weakness to be found, and the extreme weaknesses of the colour blind, with the same apparatus and the same technique, so that all the results would be strictly comparable. This is an important point. All the commonly used tests of colour blindness, such as Holmgren's Wool test, Stilling's Tables, the Ishihara test, Edridge-Green's Bead test and Lantern, fail to compare the colour blind with the colour weak or normal. They are tests for cutting out the colour blind at the danger level commonly accepted for practical purposes, and they take no account of the accurate discrimination of individual differences. None of these tests enables us to measure the normal and the colour blind accurately with the same measuring-stick. The vast weakness of the colour blind is the chief reason for this difficulty. Another difficulty is the high sensitivity of the normal. The problem in testing intelligence, on which many of our general ideas about psychological tests are based, is altogether different. Here the variability among the normal is far greater than in colour vision, and the extremes are approached by a smoothly graded series, whereas in colour vision the series is discontinuous. Hence it has never been possible to see the normal and the colour blind compared by means of a single test equally applicable to both, and it is obvious that for many practical and theoretical purposes such a comparison would be invaluable.

The Nela wools test works on the principle of a series of finely graded colour comparisons, and the result is given in terms of the number of correct distinctions made.[1] Pierce's test depends on the principle of asking the subject to set in order a series of disks of finely graded saturation difference, and the result is given in terms of the number of misplacements after the subject has set the disks in order to the best of his ability.[2] Colour-vision testing, however,

must be based on the measurement of thresholds for the perception of hue and/or saturation differences.

Houstoun's microscope test[3] might have served this purpose. Several forms of it were tried out, but it was given up as unsuitable. It is essentially a test in which the light reflected by a minute spot of colour on a grey paper, or transmitted by a minute piece of colour filter in a transparent microscope slide, is desaturated with the white light from the surrounding areas in proportion as the microscope is out of focus. It was used by the Method of Production, in which the subject adjusts the microscope, and by the Method of Limits, in which it is adjusted by the experimenter; and it was used with small squares of red, yellow, green and blue to be identified by name individually; to be seen all together in the same field and distinguished; and with a slide in which all combinations of these four colours were arranged in pairs in which each pair made a minute square half of which was of each colour, to be distinguished by the subject. It is an extremely interesting test to experiment with, but the range of variability of the settings under all the circumstances mentioned above was so great that the test was impracticable as a quick and efficient test of colour vision. Moreover, the slightest change in angle of view of the subject had a large effect on the appearance of the test objects seen through the microscope, and neither the intensity of the test spots nor that of the light which desaturated them was under control, so that a protanope, for instance, might be deceptively good at distinguishing red from yellow and green, but not from blue, thus giving a distorted picture of his defects. Looking down a microscope is tiring to the eye for the inexperienced, and not everybody is equally good at it without training. In this test it is impossible for the tester to see what the subject is looking at, yet this is an important guide for him when interpreting the subject's responses.

APPARATUS

The Rayleigh Equation experiment described in this chapter used two disks, each of eleven centimetres in diameter, fitted with black backgrounds twenty centimetres in diameter, which rotated with the disks. The standard disk was to the left, with a gap of about one inch between the disks, so that the backgrounds overlapped. The disks were mounted on two Marbe rotators driven by a quarter horse-power motor at a speed which eliminated flicker. The standard disk was composed of one 90° sector of lemon yellow paper attached to a circular white disk which was slit from the centre radially along

one edge of the yellow sector, so that a black disk, similarly slit, could be slipped through it. The trio of papers showed at one extreme only white and yellow; at intermediate points it showed combinations of white, black and yellow; and eventually the black disk covered the yellow as well as the white. In appearance it underwent a perfectly continuous change from white to black, the intermediate stages being yellows of least saturation and greatest brightness at the white+yellow end, and of greatest saturation and least brightness at the black+yellow end. The amount of variation actually employed in the tests and experiments did not exploit the extreme positions at all, and simply represented small variations in the proportions of black and white to yellow in the middle region. They were small changes in the brightness of a rather desaturated yellow. The 90° yellow sector was itself a saturated lemon, but the degree of desaturation required to match it with the red+green variable disk was three parts of grey and one part of yellow of equal brightness. The red+ green combination, although both colours were themselves saturated, therefore made a yellow three-quarters desaturated, although they were both polychromatic colours. One or two subjects were found for whom the 90° sector of yellow could not be kept constant, but had to be reduced as the red-green disk approached the green side. This was very unusual, and for these subjects a special standard disk was kept and fitted to the Marbe rotator if required. In this disk the yellow was independent and could be varied by hand if the rotator was stopped.

The variable consisted of a red and a green circle split in the ordinary way and fitted together to form a disk which could be changed from red to green through all intermediate stages. The red and green chosen were coloured papers as near as possible to the colours called pure red and green in the spectrum. Thus the green was neither yellowish nor blueish, and the red was neither vermilion nor carmine. The variable disk started pure green at one end, and passed through yellowish greens to the pure desaturated yellow, which many people called fawn, and then it became more and more orange until it ended a pure red. For all but a very small number of subjects the red was somewhat darker than the green, and the yellow-black-white disk had to be darkened to match the red-green disk continuously in passing from green to red.

A yellow-blue equation was arranged with a variable yellow and blue disk and a standard grey disk composed of a 30° sector of green diluted with variable proportions of black and white. It would have been possible to set up this test with a slightly more violet blue, which

would have been exactly complementary to the yellow. This pair would have made a grey perfectly matched with a black and white standard without the 30° sector of green. It was preferred, however, in this experiment, to imitate the Rayleigh Equation by choosing a blue and yellow not quite complementary. In practice the green-black-white disk appeared black, faintly greenish black, grey or white, according to the proportions of black and white in it. Thus, starting at the completely black end, at first the green was revealed by the black, and made a very dark desaturated green, and then the green was completely desaturated by the addition of white so that in the middle the mixture appeared purely grey, while at the other end it was perfectly white. It is true that this particular grey could not have been made without a 30° sector of green, but in practice it did not appear green in the mixtures used in the experiments, although the green in it was the exact equivalent of the extent to which the blue and yellow were not complementary.

In setting up these experiments, as in all the experiments described in this book, the plans were not settled on arbitrary rules decided beforehand, but the exact details were the result of a series of preliminary trials on a number of subjects.

Marbe Rotators enable the coloured disks to be varied while rotating. Dr. Mary Collins assures me that it is possible to do this experiment efficiently with a rotator which has to be stopped for each adjustment, but it is difficult to avoid putting greater confidence in an experiment in which the disks can be altered and the scales read without stopping the engine. In a private discussion she suggested that it was an advantage to stop the rotators to give the subject of the experiment a rest during which visual fatigue for the colours might be overcome. This might be an advantage in her experiment, in which the two disks were concentric and the subject could fixate a point on the line of demarkation between them. This would fatigue neighbouring areas of the retinae constantly in certain ways and tend to reduce the sharpness of any contrast between the variable and standard. In my form of the experiment, however, the subject must look from one disk to the other, as a result of which the same areas of the retinae are fatigued in opposite ways at every change of fixation. The contrast, if any, between the disks, is accentuated, not diminished by separating them, and fatigue for the colours is reduced, so that the technique of stopping the disks for each reading is of no advantage. The subject may rest his eyes at any time during the experiment, if he wishes to do so. The Marbe Rotator provides for readings at least as small as half-millimetres on the scale, and one millimetre

c*

corresponds to five degrees of change in the coloured disks on the one instrument and for six degrees of change on the other. They are accurately made and efficient instruments of excellent workmanship.

The coloured papers used in this experiment were : 1, the red Hering paper sent me by Dr. Collins, as used in her experiment, which reflects red, orange and some yellow and violet light; 2, the lemon yellow paper by Zimmermann, which reflects red, orange, yellow, yellow-green and green light; 3, the pure green paper by Zimmermann, which reflects yellow-green, green, blue-green and a very small amount of red light; 4, the pure blue paper by Zimmermann, which reflects green, blue-green, blue, violet and a little red and yellow-green light. The light reflected by these papers compares well with the polychromatic light transmitted by ordinary colour filters. Thus the red is complementary to blue-green, the green to purple, the blue to a yellow very slightly orange and the yellow to a blue very slightly violet. The four colours, though polychromatic, are a nearly pure red, and a pure yellow, green and blue.

The two disks were illuminated by a 60-watt pearl lamp in a holder like a motor-car headlamp which has a white enamel parabolic reflector and in which there is a frosted daylight-blue front glass. All streaks of light coming out in unwanted directions were blocked by a black cloth cover, and the lamp was placed slightly in front of the subject and below his line of vision. The subject sat at two metres from the disks, which were brightly illuminated, so that, although the room was darkened the subject did not work under conditions of dark adaptation. Two four-volt lamps with appropriate shades were arranged for the experimenter to read the rotator scales, and were provided with a special switch and turned off while the experiment was in progress.

TECHNIQUE

The technique adopted was a special modification of the limiting method which is used extensively in psycho-physical experiments. The test was begun at a ratio of red to green which the subject saw as redder than the yellow-black-white disk. The latter was now adjusted until the subject said it was darker than the red-green disk, irrespective of any colour difference. Next the yellow-black-white disk was brightened step by step until the subject said it was equally as bright as the red-green disk, and still more until he said it was brighter. This process was then reversed until it became darker again, and in this way a mid-point was obtained at which it looked equally as bright as the red-green disk. The subject was then asked

to report upon and describe any colour difference between the disks which he might see. If the red-green disk did not then appear redder, more orange, more fawn, more brown, or other colour on the red side, the whole test was started again at a ratio with more red, until it did appear redder. After the first position had been determined in this way, and the subject's name for the colour difference had been recorded, a series of similar readings was taken with smaller and smaller proportions of red and larger proportions of green, until a ratio was obtained which appeared greener when the brightness levels of standard and variable had been equalised by adjusting the brightness of the standard. The results were recorded during the experiment in three columns. The first column showed scale readings from which the proportions of white, black and yellow in the standard could be calculated; the second showed readings from which the proportions of red to green could be calculated; the third gave the subject's name for any colour difference observed, and showed equality of hue when there was no perceptible difference. These results gave the limits of the range of possible matches for hue, when brightnesses had been equalised, and the mid-point of this range, from which the deviations in the Rayleigh Equation could be determined.

The disks were then changed and the yellow-blue test was carried out in the same way, starting on the blue side and moving towards yellow, always establishing a brightness equality before the subject's report on colour equality or difference was considered. This was an absolutely vital point, as the aim of the test was to determine the range of colour matches possible for each subject while brightnesses were equal. Sooner or later, with all normal subjects, the limits of this range are reached, and a colour difference is established although equality of brightness is still maintained. Some critics may say that the whole test should have been repeated several times in a group of ascending and descending series, until an average for a number of sets of readings could be taken, which is usual with the limiting method. In the present experiment, however, nothing would have been gained by this, because it is essential to proceed with the greatest speed that is compatible with accuracy, and, since the tests described took from quarter to half-an-hour, it is clear that in a prolonged experiment the subject would have become so fatigued that the results would have been wholly unreliable.

In doing the red-green test any colour-blind subjects were detected without fail, because of the enormous range of colour matches they could accept. With all normal subjects steps of five degrees of change in the red-green or yellow-blue mixture were usually adequate, but

with colour-blind subjects it was often necessary to take steps of 25° in the red-green test.

With a very large proportion of the subjects a five degree change in red and green or yellow and blue required a change of about five degrees of black and white. Thus, after a number of subjects had been tested it was possible to use a quicker technique. After finding the brightness level for the red or blue appearing disk, it was possible to change both disks together, instead of re-determining the brightness level for each red-green or yellow-blue step. Then the subject was frequently asked to report on the brightness match, and, if not satisfactory, it could be re-determined forthwith. In testing any colour-blind persons great care was required in correctly determining brightness equality, because they unconsciously exploit brightness differences as indications of colour difference. This applies especially to those with darkened red, who always tend to call a hue redder than another, if it is darker and they suspect a colour difference.

For the most part the subjects were taken singly. Sometimes it was convenient to bring two into the room together and to test them in order, first with one set of disks and then with the other. This saved time in changing the disks and gave the subjects a rest between the two parts of the test, but care was taken to prevent the waiting subject from interfering even unintentionally by a gesture or chance remark. The disks were left in position after a test, covered with a black cloth, and the next subject tested would therefore do the two parts of the test in reverse order. Consequently on the whole as many started with the red-green as with the yellow-blue test, and practice effects were thus on the average equally distributed over the two parts.

The general import of the experiment was explained to each subject. He was shown that the disks would possibly appear the same colour at certain positions, and was told that the aim of the test was to find out how good he was at detecting any differences which might exist. With the vast majority of normal subjects no difficulty was met with at all, but occasional individuals are excessively particular and refuse to find a colour match. These are generally the most sensitive, and those who are less particular are usually slightly colour weak. The colour blind are generally more particular again, for one or both of two reasons : firstly, they may have real difficulty in being certain whether desaturated reds and greens are alike or different, and cannot easily decide, even when a normal person would hardly believe that there could be any doubt; secondly, they are often afraid of making a mistake, since they may have been

laughed at occasionally, and this may make them hesitate to admit that any two colours are exactly alike, even when they know quite well in their own minds that they themselves cannot see any difference.

Those with an obstinate fussiness over admitting equality between colours generally considered equal by the majority, are not necessarily the most sensitive. They may be merely the most obstinate.

Testing normal people under the conditions described is comparatively easy, once the psycho-physical technique has been mastered. It is always essential to avoid the use of any colour names which might suggest to the subject what he is expected to see. He must be made to offer the names and to decide between equality and difference strictly without help of any kind. In testing the colour blind these principles must be observed with the most rigid care. It is absolutely essential with all colour-weak and colour-blind subjects that no colour names may be used by the experimenter which the subject does not himself use. If the subject calls the red disk " green " and the green disk " red ", then the experimenter adopts this terminology for the time being, and shows no surprise whatever. Occasionally this is somewhat confusing, as when a subject insists on calling the yellow disk " red ", the red one " green " and the green one " yellow ", but the subject must not on any account be corrected until the test is over. Many a man has passed a colour test by noticing the way in which the tester used a colour name and drawing his own inferences. In addition, many colour-blind persons not infrequently offer a colour name as a bait, and when they see the surprise it occasions and are corrected they know where they have gone wrong. There is another reason for the avoidance of colour names except as the subject uses them. In the early stages of this work I explained to a man that the red-green disk would be varied, the yellow-black-white one adjusted to match it in brightness. He interjected, " Hold on a minute, where's the green, I don't see it!" After that I had the greatest difficulty in convincing him that the whole experiment was not some kind of hoax, because I had called a sector green which was to him light red. He almost refused to be tested unless a disk was produced which he was prepared to call green, and as he was a red-green blind man, it would have been a misfortune to have lost his results merely through the error of using a colour name unwisely. The best course is to invite each subject to name the sectors at the start of the test, to use the names as he uses them and to note them in the record book at the time.

If the subject has any peculiarity of colour vision in the tests it will be necessary to encourage him to report his experiences with

colours. Indeed, it is a good plan to ask beforehand whether the subject can remember any differences of opinion about the colours or colour names of every-day articles, and to talk about any discussions he may have had with his friends on these points. Such notes often throw much light on the effect of colour weaknesses in every-day life. Some subjects are reticent. A sharp denial sometimes betrays a need to hide some defect. Many subjects do not realise until after the test that one is interested in such small colour differences, and, indeed, what we call large colour differences necessarily appear small to the defective. Most will find this part of the experiment very interesting, and information about relatives may often be gleaned and they may be invited to come to the laboratory for a test. In general it is useless to ask if a subject's relatives are colour blind. A concrete approach is better, and it may be found that the maternal grandfather, perhaps, could not pick ripe tomatoes, or once stupidly painted a door green to match a brown house. Such points are of much interest.

However sympathetic we may be with persons who have colour weaknesses and forms of colour blindness, it is not our object in testing them to assist them to pass tests which they find difficult. We are concerned purely and simply with the problem of making an accurate measurement of their colour vision. Often the results seem unkind, but we must learn to be just and at the same time sympathetic, for nothing is to be gained by giving the benefit of the doubt to a man who, for instance, is almost certain that there is a difference between a green and a fawn skein of wool. If he can hesitate over this difference, concerning which no person with normal colour vision could for a moment have any doubt, and if he can finally decide almost with certainty or indeed with exaggerated confidence, that the difference is perceptible, then he has unquestionably a marked defect. To give him the benefit of the doubt on the ground that he was right in the end would be unjust to the normal as well as to him. Simple application of the principle of strictness would save much time and many errors, because some testers seem to have as much difficulty in convincing themselves that a man is defective as he has in distinguishing between certain tones and shades of colour. We must lend a sympathetic ear to the protests of those who are rejected in tests, and, if necessary, re-test them as often as they wish, but not give them the benefit of the doubt. In daily life many colour defectives habitually exploit the tendency of their friends to give them the benefit of the doubt, and in strict testing this pitfall must be avoided. The results are for science and not for the subject unless he wants

them, and it is not a necessary part of the test that he should be made to agree that he is defective.

OTHER PSYCHO-PHYSICAL METHODS

Many experimental psychologists may say that the " constants " or the " mean error " methods should have been used rather than a form of the " limiting method ". *For the constants method a set of positions for both disks would have to be arranged for each subject to be tested, so that they could be used in a pre-determined irregular order. This would prevent him from foreseeing the expected changes from difference to equality and back to difference again, as he often does when the limiting method is used, but it would not prevent him from guessing, even unintentionally, about the next stimuli to be presented. The need for a pre-arranged set of positions in this experiment would greatly increase the labour of testing, and, with many subjects whose colour vision was abnormal, a previous test by the limiting method would be necessary before the constants method could be applied. On the other hand results obtained by the limiting method can easily be checked by a few additional tests taken at random over the critical points, and this was done in every case where any doubt remained.

In other experimental work I have found the limiting method far outweighs the constants method in flexibility and always has the advantages of simplicity for the tester and of not confusing the subject by sudden and random changes in the variable.[5] The supposed advantages of the constants method are not sufficient to compete with the simplicity, practicability and systematic character of the limiting method for work on large numbers of subjects, many of whom have no previous experience in psychological testing, and among whom the variations of sensitivity to be found are not previously known to the tester. It is possible, though very doubtful, that the constants method may have some advantages for work with very experienced subjects who have to repeat the same experiment a large number of times.

As a practical method of testing the mean error method is as unsatisfactory as the constants method, but for different reasons. The essential characteristic of the limiting method is serial presentation of stimuli to be perceived or compared, starting with a perceptible stimulus or difference, passing through equality and proceeding to another perceptible difference at the other end. This is repeated

* For a description of these methods see Myers.[4]

as often as necessary, both in the " ascending " and the " descending " directions. The essential feature of the constants method is the irregular presentation of a pre-arranged series of differences, including both the perceptible and the imperceptible, sufficiently often repeated for an average level of perceptibility to be estimated. The essential of the mean error method is that the subject is in control and makes the adjustments for himself, usually starting with a decidedly perceptible difference and adjusting the variable stimulus until equality is just reached. This is repeated until an average point of equality can be calculated. The mean error method might be described as the obvious one, which would immediately appear best to a person untrained in psycho-physical experiments, while the constants method is the one which would appear obviously best to the person who had had much scientific training and little practical experience of psycho-physical work on a large scale. Experience does not confirm the presumptions that the mean error method is either the quickest, the most reliable or the fairest to the subject. The Marbe rotator is fitted with pulleys over which a cord may be passed for the subject to use in adjusting the disks himself, and so the mean error method could be applied to this experiment. This method, however tempting to the inexperienced, gives the subject almost unlimited opportunities to hesitate and make tentative readjustments. It is much slower and far less reliable than the limiting method. If we insist, as Houstoun did in his microscope test,[3] that the subject must not correct an adjustment once it is made, we may gain in speed, but we may commit the subject to an " error " which he himself could possibly have detected under better conditions, and it will pass for a genuine measurement. Houstoun himself shows that the range of error possibly involved in his readings was very large. To apply either the constants or the mean error method to an experiment like the present, in which both standard and variable disks had to be adjusted systematically, would be exceedingly difficult, though no doubt they could be adapted to the experiment by anybody who took the trouble. The " method of serial groups ", which is the fourth important psycho-physical method, and is essentially a modified form of the limiting method, would be even more complex in its application to this experiment.

SUBJECTS

The experiment was carried out on 103 men and 98 women who had normal colour vision or slight weaknesses, on 21 men and women

who were major red-green defectives and one man who was reasonably classed as yellow-blue blind. All the defective subjects were not obtained by chance. They will be discussed in the next chapter. Most of the subjects were students at Glasgow University, some from the Psychology Department, others from the Fire-Watching pickets, and on the whole they were about equally divided between the Arts and Science Faculties. Objections have been raised in conversation with critics, that no subjects should have been taken for this experiment except those trained in making physical measurements. But it was simply a comparison of individuals with a statistical norm on a standard procedure, like other common psychological tests. People are not trained in physical measurements before they go to an occulist, and, if a colour vision test is to be of any practical value it must be suitable for any subjects without previous special training. I have found no evidence that those with training in making physical measurements are any better at colour-vision tests than the general population, and those who have weaknesses in colour vision are most decidedly worse, even if they are trained in making physical measurements.

NORMAL AND ABNORMAL COLOUR VISION: TERMINOLOGY AND TREATMENT OF TEST RESULTS

Houstoun has shown, by his microscope test,[3] that in colour vision the ability to distinguish red from green is subject to normal variation and is well explained by the normal curve for all people with good or moderately good colour sensitivity, but that the red-green blind tend to form a well marked separate curve, connected with the main group by a small bridge. Thus the number of intermediates is smaller than the number of colour-blind subjects who form the peak of this separate curve. In other words, colour blindness is the result of a discontinuous variation, and must be the product of special causes or factors rather than an extension of ordinary colour weaknesses. My results fully support Houstoun's conclusion, but the study of colour-blind subjects will be reserved for the next and for later chapters.

At this point it will be an advantage to explain certain terms which will be used throughout, although the detailed evidence which shows that they are necessary will be given as we proceed. The term "range" or the expressions "matching range" or "range of matches" will be used to refer to that range of red-green mixtures which the subject can match for hue with the standard yellow of equal

brightness, for the range of yellow-blue mixtures which he can match with the standard grey, or for any other combination of colours used in the same way. It is, in technical terms, the double differential threshold (just noticeable difference) for colour, when brightness is held constant. The term " deviation " will be used for the difference between the mid-point of the range of matches of a given subject and the mean of the mid-points of the ranges of the normal group or population tested. In many cases it will be more convenient to refer to the subject's performance in terms of " range " and " mid-point ", than in terms of range and deviation.

The terms " normal ", " colour weak ", " deviant ", " anomalous " and " colour blind " will be used in the following ways : Normal subjects have a very small range of matches and a very small deviation, if any, and, although their ranges are so small, they generally accept the average mid-point as a satisfactory match with the standard, or, if they reject it, they do so by a very narrow margin indeed. The colour weak have a very small deviation, but a moderately large range of matches, and they very rarely reject the average mid-point as a satisfactory match. The deviants have a moderately large deviation and a very small range of matches, so that they reject the average mid-point, but by a moderately small margin. The anomalous have a small range, in general almost as small as the normal, but a very large deviation, and they invariably reject the normal mean matching point by a very large margin indeed. The colour blind have a small, moderate or even a large deviation, though not often as large as that of the anomalous, but they have a very large range of matches indeed, so that, however great their deviation it is exceptional for them to reject the normal mid matching point. If they do reject it, they are not satisfied or confident, whereas the anomalous find the normal mid matching point as absurd as their average matching point appears to the normal. The deviations found in the colour blind are very variable, and so are their matching ranges. On the other hand the normal, deviant and anomalous are relatively constant in both these respects.

In spite of the implications of Rayleigh's, Houstoun's or Collins' work, deviation is not the variable characteristic which leads from normality to colour blindness. The true intermediates between the normal and the colour blind are, as Edridge-Green suggested, the colour weak rather than the anomalous, because the outstanding feature of colour blindness is extreme range of matches (colour confusion) rather than extreme deviation. All this will be explained more fully when the results of experiments are described, but it is

necessary that the terminology should be given here. These classes, the colour weak, deviant, anomalous and colour blind are again open to sub-division: colour weakness may be in one, two or more colours; deviants may show their peculiarity in one colour or in two together, such as red and blue, but not in complementaries together; the anomalous may be abnormal in red or green, and the red anomalous do not always have the darkened red of the protanope; the colour blind may be divided for convenience into moderates and extremes, and again into protanopes (with darkened red), deuteranopes (with red of normal brightness) and deviant deuteranopes; yellow-blue blindness is occasionally found; total colour blindness (not of hysterical origin) has been reported by other workers.

Quantitative limits for these different classes of colour defect will be discussed when the statistical data have been given. The rare colour-weak subjects with very large ranges are specially interesting because they might be intermediates between normal colour vision and colour blindness. Similarly, the few red-green blind subjects who reject the normal average matching point for the population are also specially interesting because they might be intermediates between the colour blind and the anomalous. These and other types of intermediates will be discussed in due course.

In the use of the Rayleigh Equation it has been customary to express the deviations obtained as ratios of red to green or of green to red required to match the standard yellow. Houstoun[6] pointed out that the distribution of these fractions for a population tested would differ according to the use of the red or the green quantity as the divisor. He proposed that the logarithm of the ratio should be employed, since this would be unaffected by the inversion of divisor and numerator in the fraction, and Collins has followed his example.[7] Since it is absolutely essential to consider ranges as well as deviations, and to define a given subject's performance in terms of both classes of measurement at the same time, the use of fractions to express the deviations could lead only to confusion, and logarithms of fractions would be even worse. In the present experiments and tests, the quantitative data will be used to compare the performance of each individual with the mean and the variability of the population tested. In doing this the use of plain measurements will be most satisfactory. They apply to one test under strictly standardised conditions, and do not have the apparent universality of ratios and logarithms. In the rotating disks test the readings will be in degrees measured on the circular disks: an individual's range will be so many degrees of the red-green or yellow-blue mixture, and may be compared directly

with the normal or most frequent range; his deviation will be so many degrees towards the red, green, yellow or blue side of the average matching point of the population. We are not trying to make a physical measurement, but to compare individuals on a standardised test and technical procedure. If the technique and exact set-up of the test are kept strictly constant, then all persons tested may be compared directly, but no variations in apparatus or technique can be permitted once the experiment has been started. If improvements or alterations are introduced for any reason, then the test becomes invalid and must be started all over again.

Split Halves of the Tests

A criticism might be raised against the rotating disks tests, that the paper disks, which have to be changed repeatedly, may become soiled by handling, however carefully it was done, or that their colours might fade owing to exposure to light. This difficulty was met by dividing the whole group of subjects into two halves, the first and the second 50%, for each of the two tests (red-green and yellow-blue). The mean deviations for each half were calculated separately, and it was found that there was no statistically valid difference between the halves of either test. Thus it can be assumed confidently that neither soiling nor fading of the papers can have had any effect on the results.

Diagrams of Ranges and Mid-Points

Diagram II shows the frequencies of the mid matching points for all subjects. The red-green test results are shown in a continuous line and the yellow-blue in a dotted line. Colour-blind subjects are excluded. It will be noticed that the red-green and yellow-blue curves are very closely similar. The yellow-blue curve extends more in the direction of blue than the red-green does towards red, which indicates that in this form of test more people with normal colour vision are weak in blue than in red. Both curves have a tail in the other direction, the one to green and the other to yellow. This indicates that both green and yellow tend to be weaker than red and blue in subjects not colour blind or anomalous.

The frequencies of all the colour matches made by all the subjects not colour blind are shown in Diagram III. The red-green matches are shown in a continuous line and the yellow-blue in a dotted line. These curves are, of course, much more spread out than the
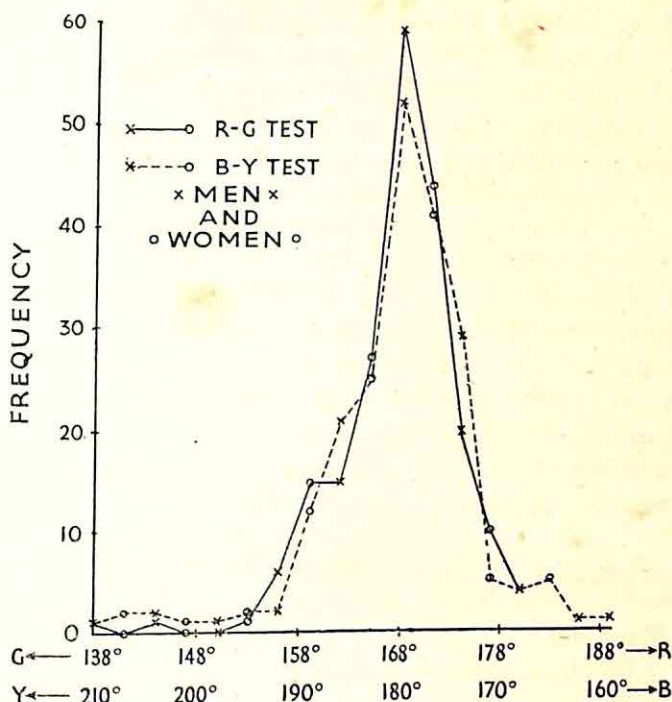
Diagram II. Rotating Disks Experiment: Mid-Matching Points in Degrees: Red-Green: 105 Men and 98 Women; Yellow-Blue: 109 Men and 98 Women
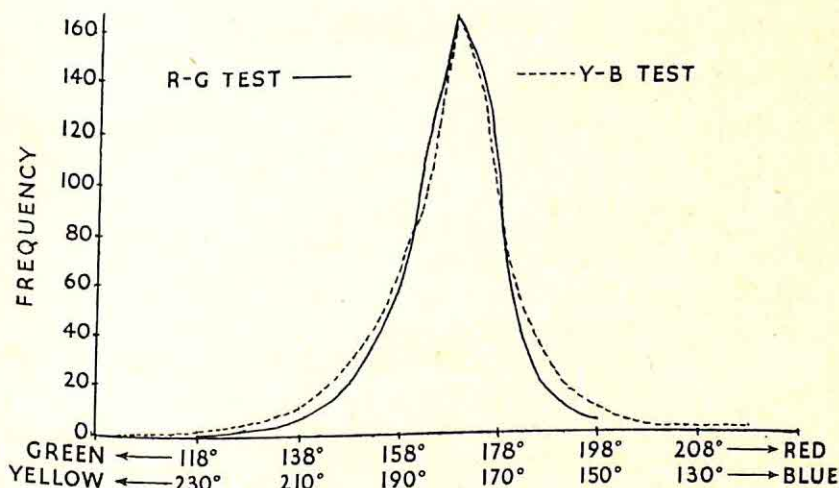

Diagram III. Rotating Disks Experiment. Colour Matches in Degrees: Red-Green: 105 Men and 98 Women; Yellow-Blue: 109 Men and 98 Women

curves of the previous diagram in which only the mid-points were shown. Again, however, the red-green and the yellow-blue curves are very nearly the same for these subjects, none of whom were colour blind or anomalous. The blue-yellow curve is more extended in both directions, indicating that these colours are more frequently weak than red and green. The curves are almost symmetrical, but there is a tail in the direction of green, showing that green is more frequently weak than red. Both curves show a tendency towards a shoulder at the right-hand side, that is to say the red and blue respectively. This might suggest that the technique of the experiment had an influence on the shape of the curves obtained, because the successive steps taken passed from red towards green and from blue towards yellow. The shoulders on the curves might indicate that the subjects were inclined to anticipate the change from " redder " or " bluer " to " equality ", and also the subsequent change from " equality " to " greener " or " yellower ". However, curves obtained in later experiments, in which several variations of technique were introduced, still showed the same tendency for shoulders on the red and blue sides, and therefore it is more likely that these shoulders indicate true characteristics of colour vision rather than effects of the technique.

Diagram IV shows the frequencies of all matching points for all subjects in the red-green test, including the colour blind and the anomalous subjects. It must be remembered in studying the curve, that 19 red-green blind subjects, 5 of whom were women, would not
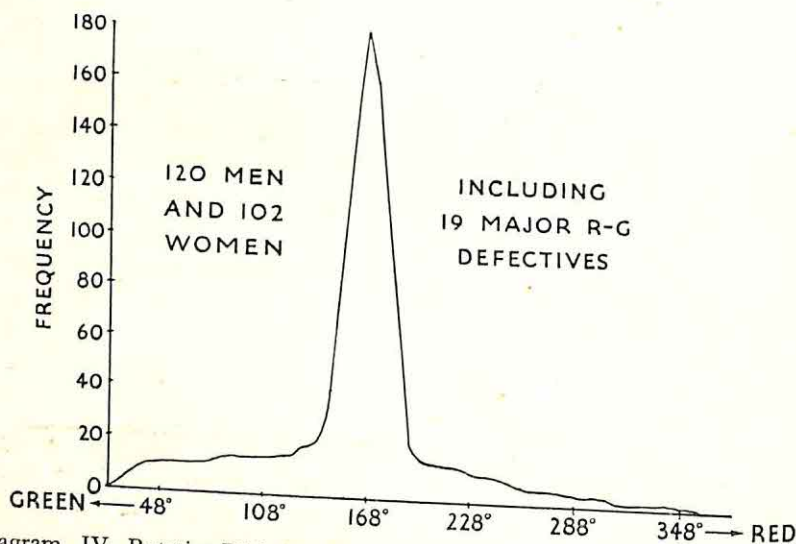

Diagram IV. Rotating Disks Experiment : Red-Green Colour Matches in Degrees

be found by chance in a sample of 120 men and 102 women. The frequency of major red-green defects is about 7% among men,[8,9,10,11] as a conservative figure, and less than 0.5% among women. To obtain 14 red-green defective men and 5 red-green defective women about 200 men and 1000 women would be required. In order to grasp the true relationship between red-green defectives and the rest of the population, therefore, the reader may imagine what this graph would look like if the base remained as it is and the narrow central peak were about six times its present height. The base would then represent the colour blind and the tall peak the normal population. Such a graph, and other similar graphs, which will be given later, strongly support Houstoun's view that red-green
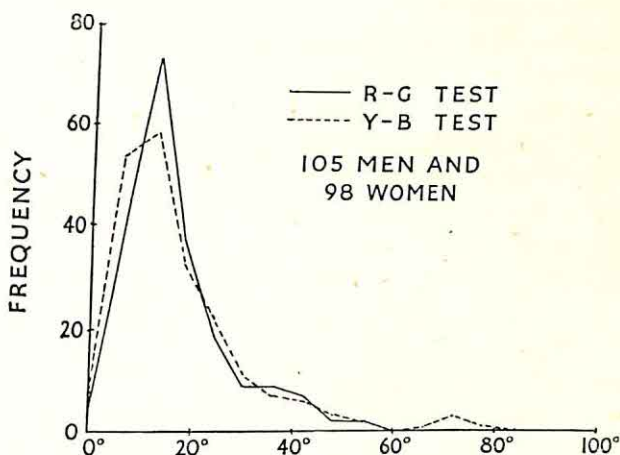
Diagram V.   Rotating Disks Experiment :   Matching Ranges in Degrees

blindness is a form of variation discontinuous with the variations of normal colour vision, and confirm the truth of the results of his microscope test although they were subject to a large amount of random error.

The frequencies of different matching ranges for normal subjects are shown in Diagram V. The continuous line shows the red-green ranges and the yellow-blue ranges are shown by the dotted line. It will be seen that the modal range is the same for red-green and for yellow-blue tests, and that the curves almost coincide up to a range of about 60° of change in the colour mixture. Beyond this limit the red-green ranges would extend to more than 300° if the colour-blind subjects were included, but the inclusion of these subjects would not change the distribution of yellow-blue ranges. In the diagram shown it will be noticed that the distributions of ranges in both tests are

strongly skewed, there being more subjects with fairly large ranges than with very small ranges. Indeed, extreme sensitivity is rarer than moderate weakness, when considered in terms of mere measurement, although, of course, from the statistical point of view the moderate ranges represent the normal condition, while both extreme sensitivity and extreme weakness are statistical abnormalities.

· DEVIATIONS AND MID-POINTS

Table 7 shows the distribution of mid-points for the red-green test, grouped according to approximate multiples of their standard deviation. The multiples are approximate because the standard deviation is a fraction, but no measurements of less than one degree were recorded. This table makes it clear that subjects may be

TABLE 7

SUBJECTS IN THE RED-GREEN ROTATING DISKS TEST, GROUPED ACCORDING TO MULTIPLES OF THE STANDARD DEVIATION OF MID-POINTS

	"Normal": Less than 1 × sigma	"Deviant": 1 × sigma or more but less than 2 × sigma		"Extreme Deviant": 2 or more but less than 3 × sigma		Totals
	161°-176°	152°-160° RED	177°-185° GREEN	143°-151° RED	186°-194° GREEN	
MEN ..	81	10	12	0	0	103
WOMEN ..	84	4	10	0	0	98
TOTALS ..	165	14	22	0	0	201

classified conveniently as "normal", "deviant" or "extreme deviant" according to the standard deviations of the mid-points. Anomalous subjects are much more extreme and could not be included in this table. If the mid-point of the subject differs from the mean of all the mid-points by less than the standard deviation in either direction, then he may be called normal; if it differs by one or more times but less than twice the standard deviation, then he may be called a deviant; if it differs by two or more times but less than three times the standard deviation, then he may be called an extreme deviant.* If the deviation is much more extreme than this he will be anomalous. This classification does not take matching ranges into account, so that a number of these deviants will also be colour-weak, but not necessarily those with the largest deviations, and some colour-weak subjects have no deviation. In this test there were about

*The distinction between deviant and extreme deviant was given up afterwards.

80% of normal subjects, and about 10% each of red and green deviants. This distribution does not differ significantly from a normal distribution, in which the expected frequencies would be 68% normal and 16% each of red and green deviants. The figures in Table 7 suggest that women are less frequently deviant than men and that they are more frequently green than red deviants. If we calculate Chi-squared on the assumption that, were there no such differences, the 14 women deviants would be distributed in the same way between the green and red deviant classes as the men, then the probability of obtaining the observed distribution by chance is between 2% and 3%, and not statistically significant. In the same way the proportion of women deviants does not differ from the proportion of men deviants by a margin which even approaches statistical significance. Women are as often red as green deviants and as often deviant as men. Hence we may conclude that this condition is not due to sex-linked inheritance, though the question of heterozygotes will be raised later. This is one of the most important reasons for treating deviants separately from the anomalous, a distinction not made by earlier workers,[7] who reported far more "anomalous" subjects. Many of their "anomalous" must have been marked deviants covered by the normal curve; others were probably colour-weak subjects who had happened to choose rather extreme matches when tested.

Table 8 shows the frequencies of deviations in the yellow-blue test, again grouped in approximate multiples of the standard deviation. In this table it will be seen that again about 80% of the subjects

TABLE 8

SUBJECTS IN THE YELLOW-BLUE ROTATING DISKS TEST GROUPED IN MULTIPLES OF THE STANDARD DEVIATION OF MID-POINTS

	"Normal": Less than 1 × sigma	"Deviant": 1 or more but less than 2 × sigma		"Extreme Deviant": 2 or more but less than 3 × sigma		Totals
	172°-188°	189°-196° YELLOW	164°-171° BLUE	197°-205° YELLOW	156°-163° BLUE	
MEN	80	9	8	5	1	103
WOMEN ..	85	5	6	1	1	98
TOTALS ..	165	14	14	6	2	201

are normal in yellow and blue, about 7% are yellow or blue deviants and a smaller proportion are extremely deviant. Again, women do not differ significantly from men. An important point is that there are no yellow or blue anomalous subjects. Evidently small yellow-

blue deviations are not sex-linked and there are no subjects corresponding to the sex-linked group of red and green anomalous men.

There is no simple correspondence between the red-green and the yellow-blue deviants—the yellow or blue deviants are not necessarily the same subjects as the red or green deviants. In other words, marked weakness in any one of these four colours may occur independently of weakness in any other colour. This conclusion will be confirmed when correlations between colour weaknesses are discussed.

Of the six yellow and two blue extreme deviants, it is interesting to record the following notes. The most blue deviant man did not know of his weakness before doing the test, and was then unable to understand how he came to make this unusual response. On re-testing there was no improvement. Of the six yellow extreme deviants, one man, on being confronted with his peculiarity, said, " Oh! Yes, I knew long ago that I sometimes confused yellow and white ". The others knew of no defect, nor did one of the blue extreme deviants, but the other confided later in a private conversation that he had sometimes thought a dark blue book cover was black. The yellow extreme deviants do not have any difficulty with the blue-yellow plates in Stilling's Tables, because they see the yellow figures as almost white, which is still clearly different from blue. They have great difficulty with the blue-green plates, but so do many people with no detectable weakness in yellow. The blue extreme deviants can also read the blue-yellow plates easily, because the blue, which is for them slightly more grey than for the normal, is still clearly distinct from the yellow. They also have difficulty with the blue-green plates, but, again, many people with little or no weakness in blue find them confusing, and they are a very unreliable guide.

When colour blind and anomalous subjects are excluded sex-differences are very small indeed. Collins concluded that extremely abnormal colour matches in the Rayleigh Equation were not found among women.[7] No doubt the extreme men in her equations were anomalous subjects. Anomalous colour vision is a sex-linked character, and is found in a small number of women who inherit a defect from both sides of the family and in whom a defective gene is present in each of the X chromosomes. Ordinary deviations, however, appear to be as common among women as among men, though the figures given above suggest that men are inclined to be slightly more variable than women. Table 9 shows the standard deviations (sigmas) of the mid-points of men and women in the red-green and the yellow-blue tests, together with the differences between the standard deviations

and the standard errors of these differences. These differences are both statistically significant and show that men tend to be more scattered in both tests than women, anomalous subjects and colour blind excluded.

TABLE 9

DIFFERENCES BETWEEN STANDARD DEVIATIONS FOR MEN AND WOMEN

	Red-green sigma	Yellow-blue sigma
Men	6·60°	8·48°
Women	4·78°	5·81°
Difference	1·82°	2·67°
S.E. Diff.	·57°	·71°
Diff./S.E. Diff.	3·19°	3·76°

MATCHING RANGES

Table 10 shows the ranges of matching in the red-green test, of all subjects except the colour blind, whose ranges are so great that they cannot be readily included in the same table. The ranges for men and women in both tests can be compared. It will be seen that the distribution of ranges is strongly skewed. The modal range for

TABLE 10

HALF-RANGES OF MATCHING IN THE RED-GREEN AND YELLOW-BLUE TESTS FOR MEN AND WOMEN

		Half-Range of Matching in Degrees													
		Less than 1	2–4	5–7	8–10	11–13	14–16	17–19	20–22	23–25	26–28	29–31	32–34	35–37	38–40	Totals
R and G	M.	2	19	36	24	11	4	2	4	0	1	0	0	0	0	103
	W.	2	22	35	13	8	5	7	3	2	1	0	0	0	0	98
Y and B	M.	5	26	31	14	12	7	3	5	2	2	0	0	2	0	109
	W.	1	27	27	19	10	4	4	1	2	0	0	1	1	1	98

men and women in the red-green test is 5—7 degrees, and it is almost the same in the yellow-blue test. There are no fractions of degrees in the readings. There is a decided tendency for the number of large ranges to be greater in yellow and blue than in red and green. In other words there is a tendency for more yellow-blue weak than red-green weak subjects. This was confirmed by all subsequent experiments. In the yellow-blue distribution four red-green blind

and two green anomalous men subjects who fell into the sample of 109 by chance have been included, because they do not have corresponding weaknesses in yellow and blue. It is convenient to regard all subjects with more than twice the modal range as showing a decided weakness in the colours in question. This criterion has been chosen because it is statistically convenient and also corresponds well with the level of colour weakness which has a noticeable effect in daily life. If we take this level as satisfactory, then there are eleven men and 18 women who can be called red-green weak, whether or no they have a marked deviation in the Rayleigh Equation. This sex difference has a probability between 0.02 and 0.01 by the Chi-squared technique, and very strongly suggests that women are more often red-green weak than men, excluding the anomalous and colour blind. It will be seen in the next paragraph that there is probably a good reason for this sex difference. In the yellow-blue test there are 21 colour-weak men and 14 colour-weak women, but here the probability is between 0.10 and 0.05, and cannot confidently be regarded as of any significance. This corresponds with the finding that yellow-blue weaknesses are not sex-linked.

INDIVIDUAL SUBJECTS

Twice the modal range is a considerable colour weakness, and is often noticeable in daily life, while it may be detected sometimes by ordinary tests for colour blindness, though not with certainty. The bigger the range the more liable the subject will be to make slight colour matching and naming errors. The Ishihara Test, and others like it, are not sufficiently sensitive to detect ordinary small colour weaknesses with any degree of reliability, and the blue-green plates in Stilling's Tables are equally unreliable for the detection of small yellow-blue weaknesses. The Ishihara Test fails the colour blind and the true red or green anomalous subjects, and, if it is applied very strictly, a certain proportion of subjects with small colour weaknesses will be failed as well, but in a wholly unreliable manner.[12,13] Collins[14] has claimed that it is moderately reliable for detecting subjects with very small colour weaknesses, but I have not been able to support her claim.

One woman subject who is both red-green and yellow-blue weak, has a peculiar system of colour naming. The term " shade " she uses both of brightness and of colour differences which are very small and hardly perceptible. A pinkish and a greenish grey would differ in " shade " if very little different in colour, and two greys of

identical hue would also differ in " shade " if one were very slightly darker than the other, but if they were markedly different in hue they would be said to differ in colour. This is an example of the tendency which will be found more freely among the colour blind, to use brightness differences as guides to differences of colour which are imperceptible for them. A slight change of hue would often be accompanied by a slight brightness difference. By exploiting the term " shade " in two senses she was able to guard herself (though quite unintentionally) against the possibility that other people might notice her slight difficulty in correctly naming very desaturated colours. She admitted this when it was pointed out to her. Another subject, who has a very marked blue-yellow defect also has the violet end of the spectrum much darkened.[15] Darkened violet does not amount to a selective violet blindness, any more than the familiar darkened red of the protanope amounts to a selective red blindness, because her defect is in both yellow and blue, just as the defect of the protanope is in green as well as in red. She has great difficulty in seeing the violet end of the spectrum, from the blue part onwards to the end, but this is coupled with a marked weakness in yellow. Other examples of darkened violet vision will be given later.

A third woman subject who has no measurable defect in red and green or in yellow and blue in central vision, was found to call a red test-object of five millimetres diameter " green " in peripheral vision during an experiment on colour perimetry, at an angle at which other people had no doubt of its being red. She was surprised to find it red in central vision. She had a difficulty in finding green in a demonstration spectrum in slightly oblique vision, and reported calling the green jacket of a friend pink by mistake, when it, too, was seen in oblique vision. It was clear that her colour vision was abnormal, and she was asked to inquire of her mother if her father had ever shown any kind of abnormality in naming or matching colours. Her mother reported that her father always had a difficulty in seeing red poppies in a corn field, and he came to the laboratory and proved to be decidedly red-green blind, and for this defect the daughter was certainly heterozygous. His colour vision will be discussed later. This example indicates the importance of a more thorough study of peripheral colour vision.

A fourth woman subject, who is a blue deviant, reported that she had a difficulty in distinguishing " near shades " of blue and green, tending to call them green rather than blue. Later it will be seen that this tendency almost always accompanies blue weaknesses. These notes about individual subjects give a good idea of the extent

to which the effects of small defects in colour vision tend to be apparent in daily life.

WOMEN WITH COLOUR-BLIND RELATIVES

The majority of red-green blind and anomalous men are the offspring of matings between normal fathers and mothers who are heterozygous for the defect. Other matings can produce defective men, of course, but they are much less frequent, because they involve colour-blind parents. In the study of a totally sex-linked recessive character, such as red-green blindness, a simple calculation should enable us to determine the proportion of homozygotes and heterozygotes in the female population, if we know the proportion of males who show the recessive character.[17] Let this proportion be $p\%$ and the remaining proportion of males who are normal be $q\%$. Then the proportions of recessives, normals and heterozygotes in the female population will be as shown in Table 11, if we assume the single locus theory of inheritance, which will have to be reconsidered in Chapter X, and is almost certainly untenable.

TABLE 11

PROPORTIONS OF NORMAL AND RED-GREEN BLIND IN THE POPULATION, AND OF HETEROZYGOUS WOMEN

(on the single locus theory)

MALES		FEMALES		
Normal	Col. Bl.	Normal	Heterozygotes	Col. Bl.
p	q	p^2	$2pq$	q^2
93%	7%	86·49%	13·02%	0·49%

Here it is taken that the proportion of red-green blind men, including all types of deuteranopes, protanopes and red and green anomalous, is about 7%, which, though rather variable in different districts as Vernon and Straker have shown,[8] is a fair average figure, and accords with the results of the present experiments. In other words, every seventh or eighth woman we meet must on the average be capable of having a colour-blind son.

In the past it has generally been assumed that these heterozygous women are perfectly normal, in other words, that red-green blindness is a recessive in Mendelian terms, and that if one X chromosome carries the normal (dominant) gene, there will be no defect. However, the frequency of red-green defective women has sometimes appeared

greater than the expected 0.5%, and it has been suggested that red-green blindness is not completely recessive. This would accord with certain findings of the present experiment, where one or two women who must have been heterozygous were almost weak enough to be classed as defectives. Clearly, such heterozygous women would not be detected by the study of deviations in the Rayleigh Equation, because there is very little difference in the numbers of deviants in the two sexes, and, if anything, men tend to be more scattered than women in their deviations. In the ranges of matching, however, women are distinctly more often colour weak in red and green than men, but there is no difference in yellow and blue. There is in consequence the possibility that some of these colour-weak women are heterozygous.

In order to test this hypothesis all the women tested who knew that they were related to red-green blind or anomalous men or women were picked out and are classified in Table 12. On the basis of purely chance selection this method would not discover them all, because a proportion would not know of defective relatives who did exist, others who were heterozygous would have no sons, and others also heterozygous might have inherited the condition for any number of generations down the female side without a male colour-blind relative appearing—though this is not likely to be very common. For example, if Julius Caesar was colour blind one of the women in my 98 might have inherited the heterozygous condition from his daughter (if he had one) continuously down the female side. Table 12

TABLE 12

NUMBERS OF WOMEN CLAIMING COLOUR-BLIND RELATIVES

	Daughters	Sisters	Mothers	Cousins	Total
Normal Women ..	5	4	0	1	10
R-G Weak Women ..	3	7	1	0	11
Y-B Weak Women ..	0	2	0	0	2

shows the relationship claimed, whether sister, mother, daughter or cousin. The table also shows whether the woman claiming the colour-blind relative is herself colour weak. Thus out of 23 women who were known to claim red-green blind relatives, eleven were red-green colour weak and two yellow-blue weak. It would not be expected to find 23 such claimants in a sample of 98 women by chance,

but three of these were invited because they were known to have such relatives. It is interesting to compare these frequencies with the numbers of colour-weak women in the group as a whole : there were 18 red-green and 14 yellow-blue weak women among the 98 tested. Thus it is known that 11/18 red-green weak, but only 2/14 yellow-blue weak women in a group of 98 were related to red-green blind persons. We do not know whether the remaining 7 red-green weak women had red-green blind relatives, but so large a proportion as 11/18 could not be arrived at by chance. This is shown in Table 13, for which Chi-squared is about 48, and the probability of obtaining this distribution by chance is therefore exceedingly minute.

TABLE 13

WOMEN WITH COLOUR-BLIND RELATIVES

	Relation to Colour Blind claimed	No relation to Colour Blind claimed
R-G Weak Women	11	7
Normal Women	10	70

It may be claimed on the strength of this table that women with colour-blind relatives are much more often colour weak than other women. Every woman who is the daughter or mother of a colour-blind man or woman, and who is not herself colour blind, must be heterozygous for the defect, and those with colour-blind brothers or cousins may be heterozygous. It is therefore certain that most of the eleven red-green weak women listed in Table 11 were heterozygotes for red-green blindness. Many of those who claimed no defective relative may also be heterozygous, and it is clear from the table that yellow-blue weakness does not correspond to this condition. Men, however, may be as colour weak as women, without being colour blind, and, since they have but one X chromosome, they must be colour blind if they inherit the defective gene at all. Red-green weakness, therefore, is not necessarily indicative of the heterozygous condition. While we may say that many heterozygous women are measurably colour weak in red and green, but not in yellow and blue, all such colour-weak women are not necessarily heterozygotes, and all heterozygous women are not necessarily colour weak. So far as these results indicate, therefore, we are not in a position to detect heterozygotes by the rotating disks test with certitude, though we can do so with a considerable degree of success. It would be an interesting experiment to collect a sample of 50—100 women known

to be heterozygous for red-green blindness, because their fathers, mothers or sisters were known to be colour blind, and to compare with their red-green ranges those of as many normal men.

CORRELATIONS BETWEEN COLOUR WEAKNESSES

In order to find the degree to which colour weaknesses in the four colours red, yellow, green and blue were dependent on each other in the subjects tested in this experiment, calculations were made in the following way: The weakness of an individual subject in a given colour was taken as the measurement in degrees, from the mean for the whole group of the mid-points of the pair in which that colour appears, to the point at which he just discriminates that colour from the standard disk of equal brightness. This measurement of colour weakness takes both deviation and range into account. Colour weaknesses measured in this way are normally distributed, and they are the only practicable basis for direct comparisons between degrees of sensitivity in all the four colours tested by the technique of this experiment. Thresholds for individual colours, measured against a grey standard, would appear to be more satisfactory in theory. Most of the measurements of colour weakness made in the way described above are negative quantities, they express the subject's differential threshold as being at a point which is -x degrees from the average mid-point, and the sum of his weaknesses in colours measured in pairs is equal to his matching range in those colours (omitting the negative signs). In the case of subjects with small ranges and large deviations, however, one of the measurements may be positive and the other negative. This will happen wherever the range does not include the average mid-point of the normal group. If the signs of the two measurements are reversed, then the algebraical sum of his measurements of weakness in two colours taken as pairs in the experiment will still be equal to his matching range in those two colours. " Positive " colour weaknesses have been criticised because they represent strength rather than weakness, and we have no means of showing that a red deviant, for example, is more sensitive than the majority to green though there is often another way of showing that he is less sensitive to red. However, the experiment measures relative strength and weakness and, on the whole, the more colour weak a person is, the greater the negative measurements of weakness, but the more deviant he is in a given colour the more he tends to have positive measurements of " weakness " in the other colour of the same pair, and the larger those measurements tend to be. These

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positive measurements are mathematically of an arbitrary nature, because, for the purpose of calculating correlations it is equally easy to measure colour " weakness " from either end of the scale (as a zero) to the point where the given colour is just perceptibly different from the standard of equal brightness. All measurements are now positive, but the result of correlating them is exactly the same as obtained by the other method. From the point of view of colour vision, however, these positive measurements of " weakness " are not arbitrary : they express the extent to which deviation outbalances range, and this is an essential characteristic of colour-vision variations in certain individuals. Implications of this problem will be discussed again later.

The interest of correlations was not limited to colour sensitivities. Measurements of the brightness level of the red-green and yellow-blue pairs were taken throughout, and varied from one individual to another. The red and blue papers were darker for everybody than the green and yellow, and in consequence the changes in proportion from redder to greener and from bluer to yellower both required brightening of the standard step by step. The rate of brightening, however, was variable from one individual to another and the starting points in the series of measurements taken were also different. Part of the variability of the measurements was therefore due to the varying reflectivity of the combined red-green or yellow-blue disk, as the ratio of red to green and of yellow to blue changed. In order to eliminate this source of variability, in which there was no interest for the immediate purpose of the test, it was necessary to take fixed proportions of red to green and of yellow to blue as the proportions against which brightness levels for different subjects should be estimated. It is generally known that brightness equalities are more easily estimated between identical than differing colours or colours and greys. Since not all the ranges of identity for colour matching with the standard of equal brightness overlapped, in each experiment taken separately, this ideal condition could not be fulfilled, and it was necessary to take the nearest possible. For this purpose the most suitable fixed ratio of red to green or of yellow to blue for brightness estimation was the proportion most frequently identified with the standard yellow for the red-green test or grey for the yellow-blue. A sufficiently large set of readings had been taken for this to be possible for every subject, however great his deviation, and in this way the most reliable estimate of brightness level of the pair of colours in question was obtained, although there was in some cases a small colour difference, which may be assumed to have had no

appreciable effect on the results in general. Hence, in order to determine each subject's brightness level for a given pair of colours, the size of the black sector required by him for brightness matching at the average normal mid-point was taken.

If a subject is weak in a given colour, then, on the Young-Helmholtz theory, his brightness level for that colour and for all colour mixtures in which it appears as a component must be lowered, and this lowering must be proportional to his colour weakness. This is unavoidable on that theory, because brightness is wholly determined by colour responses and not produced in any other way in daylight adaptation. Hence there should be a very high correlation between brightness level and colour weakness. There is, however, the difficulty that the brightness of the red-green or the yellow-blue disk at the proportion chosen for measurement, which was the average normal mid-matching point, or at any other proportion, will depend partly on each of its two components. Hence it was necessary to adjust the correlations obtained by the usual method of partialling out and holding constant the irrelevant variable, namely, in this case, the influence of the colour in each pair other than that for which the correlation for brightness level is required. In practice it turned out that the correlations with brightness level were so small that this made very little difference.

Correlations were worked out for men and women separately, excluding colour blind and anomalous subjects, for the four colours red, yellow, green and blue, and between each colour and the measurement of brightness level of the pair to which it belonged with the effect of the other colour partialled out. These intercorrelations are shown in Tables 14 and 15.

In these tables correlations above 0.23 may be considered significant on the 0.02 level and those above 0.254 may be considered significant on the 0.01 level. In Table 14 there are no significant

TABLE 14

INTERCORRELATIONS BETWEEN COLOUR WEAKNESSES
(Colour Blind Excluded)

	103 *Men*	98 *Women*
R and G	−·30	+·21
R and Y	+·19	+·21
R and B	+·15	+·25
G and Y	+·16	+·31
G and B	−·09	+·08
Y and B	−·18	+·18

TABLE 15

PARTIAL CORRELATIONS BETWEEN COLOUR WEAKNESS AND BRIGHTNESS LEVELS

(Colour Blind Excluded)

	103 Men	98 Women
R and Brightness	—·15	+·23
Y and Brightness	—·04	+·13
G and Brightness	—·13	0·00
B and Brightness	—·13	—·29

correlations except those between red and green for men (negative) and those between red and blue and between green and yellow for women (positive). In Table 15 the partial correlation between red and brightness (positive) for women is almost significant, and that between blue and brightness level (negative) is decidedly significant. For men there are no significant correlations for brightness level.

The general conclusion may be drawn from these figures that there is very little relationship between variations in sensitivity to any of the four colours, or between such variations and differences in brightness level of colour mixtures containing the colour in question. This conclusion tends to emphasise the independence of the four colours tested, including yellow, and of brightness changes, and it lends no support to the Young-Helmholtz theory or any other three-component theory, or to any theory in which brightness is determined wholly by hue sensitivity. The same problem as it applies to the colour blind will be discussed in the next chapter. The factorial analysis of intercorrelations between colour sensitivities will be discussed later.

Chapter 3

THE ROTATING DISKS EXPERIMENT: ANOMALOUS AND COLOUR-BLIND SUBJECTS

THIS chapter will be devoted to the study of the colour blind and anomalous subjects, including the one extremely yellow-blue defective man, who did the rotating disks experiment. These subjects all did the Ishihara Test, Stilling's Tables, and other colour-vision tests, such as Holmgren's Wools, Edridge-Green's Beads and Lantern, and Nagel's Card Test. All were asked the most detailed questions about the extent and nature of any difficulties which they had with colours or shades in daily life, and any other relevant information which could be collected about them was noted in the test booklets at the time or later. All this information has been thoroughly examined and is expressed in the form of generalisations for the help of the reader, but it must be emphasised that these generalisations are based on the detailed study of individuals. Examples of the colour vision of particular subjects have been given at the end of the chapter, and colour-blind women have been selected wherever possible, because they are much rarer than colour-blind men and some people even doubt their existence.

DISTRIBUTION OF WEAKNESSES

Diagram VI shows the ranges of matching in (a) the red-green test and (b) the yellow-blue test, for 14 red-green blind men, of whom six are protanopes; 5 red-green blind women, two being protanopes; 2 green anomalous men, one extreme green deviant man; one colour weak woman, sister of the two women protanopes, and one yellow-blue defective man. The modal matching points have been made to coincide for the red-green and the yellow-blue tests, that is, 180° for the yellow-blue test coincides with 168° for the red-green test. The ranges are shown for individual subjects, red-green by continuous lines and yellow-blue by dotted lines. Circles represent women and crosses represent men.

From the results shown in this diagram the following conclusions may be drawn. First, that the colour-blind subjects cannot be divided

into "red - blind" and "green - blind". Both protanopes and deuteranopes are weak in red and in green together. Indeed, it is probable that protanopes are actually more able to distinguish red from an equally dark and desaturated yellow than the deuteranopes are able to distinguish green from a yellow matched with it in brightness and saturation.

The second conclusion, that red-green ranges do not correspond to yellow-blue ranges in magnitude in the same subjects, confirms what has been said for normal subjects on the basis of correlations between colour weaknesses. Similar correlations for the red-green blind will be discussed later.
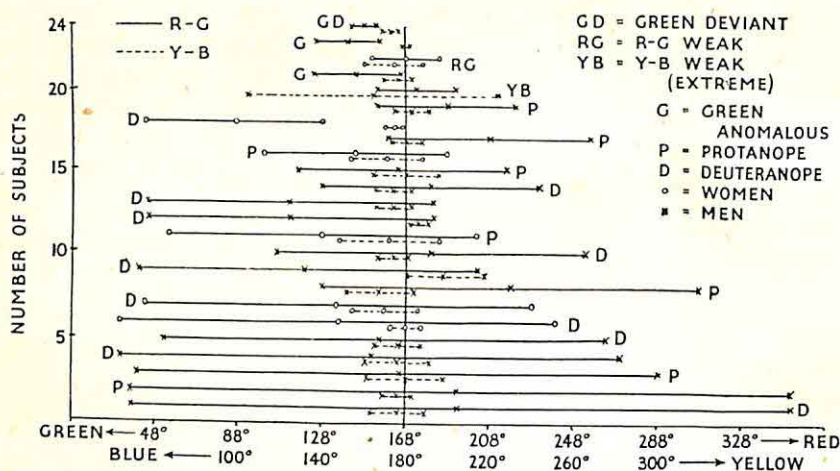

Diagram VI. Rotating Disks Experiment: Matching Ranges for Defectives, in Degrees

In the third place, it is clear that there is a continuous gradation of weaknesses from the most extreme, for whom no degree of red or green saturation can make either of these colours different from a yellow of equal brightness, to the least extreme, for whom both red and green are distinguishable from such a yellow if they are sufficiently saturated. The least extreme of the red-green blind are, however, vastly less sensitive to the distinction between red and green than the weakest of normal subjects.

The fourth conclusion from the diagram of colour weaknesses in the colour blind is that deviation in at least this form of the Rayleigh Equation is little or no guide to the class of colour blindness of the subject in question. Four protanopes have red and four have green deviations. Three deuteranopes have red deviations and eight

have green. Application of the Chi-squared test shows that this is not significantly different from a purely chance distribution. This again supports the view that protanopes and deuteranopes are not to be regarded as " red-blind " and " green-blind " respectively, but are both red-green blind, and either class may be relatively more weak in red than in green or in green than red, when measured against a yellow of equal brightness. The difference between them is that in protanopes the red is greatly darkened. The disks test, being based on polychromatic colours, does not bring out this darkening so sharply as tests with monochromatic filters to be discussed later.

With one exception, all the colour-blind subjects are able to accept the normal Rayleigh Equation as one matching-point in their ranges. This subject is a greater deviant than the average green anomalous subjects, if deviation alone is to be taken as the criterion. Owing to her wide range, however, she is much more colour blind than any anomalous subject, and, indeed, she is more colour blind than the least red-green blind of this group. She will be classed as a " deviant " deuteranope and not as anomalous. Thus the fifth conclusion is that we can have four classes : (a) red-green blind, divided sharply into (i) protanopes and (ii) deuteranopes, and (b) anomalous, who are not colour blind but may be (i) red anomalous or (ii) green anomalous. Apparent intermediates, who are extremely deviant and reject the normal mid matching point although their range is so great as to force us to call them colour blind, are rare, but show characteristics, such as the tendency to confuse red and green, which distinguish them from the truly anomalous. This experiment showed therefore not less than four sub-classes of major red-green defect, and there is no doubt that these are all inherited on a sex-linked basis, while they are also inherited true to type so far as we can tell. They appeared in the following proportions : protanopes 8; deuteranopes 11; green anomalous 2; red anomalous 0. This group of 21 major red-green defectives, however, could not satisfactorily be called a random sample of such subjects, because three were immediate relatives of two of the others. A better indication of frequencies will be given later.

Finally, the one yellow-blue blind subject showed as big a range in yellow and blue as many of the red-green blind show in red and green, and, like them, he is weak in both colours together, having a big range and a small deviation. Hence he does not fulfil the expectations based on the Young-Helmholtz theory, that a " tritanope " should be blue blind rather than yellow-blue blind, and that a person cannot

have a big weakness in yellow without at the same time having correspondingly big weaknesses in red and green. Since there are other subjects shown in Diagram VI who have bigger ranges in red and green than he, and who are not correspondingly weak in yellow and blue, his yellow-blue blindness cannot be attributed to his small red-green weakness. The nature of his defect therefore lends no support to the Ladd-Franklin theory, on which it would be predicted that a person cannot be yellow-blue blind without also being red-green blind.

CORRELATIONS BETWEEN COLOUR WEAKNESSES

Colour weaknesses for the red-green blind subjects were measured in the same way as described for the normal subjects in the last chapter. Correlations between these colour weaknesses were then worked out for nineteen colour-blind subjects by the rank difference formula. They are shown in Table 16. Similarly, correlations between colour weaknesses and brightness levels for the corresponding colours were worked out and are shown in Table 17.

TABLE 16

CORRELATIONS BETWEEN COLOUR WEAKNESSES :   14 RED-GREEN BLIND MEN AND 5 RED-GREEN BLIND WOMEN

Red-Green	+ ·15
Red-Yellow	− ·04
Red-Blue	+ ·24
Green-Yellow	+ ·11
Green-Blue	+ ·08
Yellow-Blue	+ ·16

TABLE 17

CORRELATIONS BETWEEN COLOUR WEAKNESSES AND BRIGHTNESS LEVELS : 14 RED-GREEN BLIND MEN AND 5 RED-GREEN BLIND WOMEN

Red and Brightness	+ ·12
Yellow and do.	+ ·10
Green and do.	+ ·26
Blue and do.	+ ·25

These correlations, both between colour weaknesses themselves, and between colour weaknesses and brightness levels, are all very small, and, according to Fisher's table of values of correlation coefficients for different levels of statistical significance, none of

them is significantly different from zero. It is important to notice that, even in this series of red-green blind individuals, neither red nor green weaknesses are correlated with yellow weaknesses, nor are red and green weaknesses correlated with reduction of brightness levels of the same colours.

DIFFERENCES OF MEANS FOR COLOUR WEAKNESSES

Table 18 shows the mean colour weaknesses of 98 women and 102 men who were either normal, deviant or colour weak, and 14 men and 5 women who were red-green blind, in the rotating disks experiment. The differences of the means for each of the four

TABLE 18

DIFFERENCES BETWEEN COLOUR WEAKNESSES FOR RED-GREEN BLIND AND " NORMAL " SUBJECTS IN THE ROTATING DISKS TEST

	102 *men* + 98 *women*	14 *C.B. men* + 5 *C.B. women*	*Diff.*	*S.E. Diff.*	*t*
Red	7·5°	72·0°	64·5°	13·2°	4·89
Green	7·5°	97·0°	89·5°	10·1°	8·86
Yellow	7·7°	9·0°	1·3°	1·9°	0·68
Blue	7·5°	14·0°	6·5°	2·0°	3·25

colours, together with the standard errors of those differences and the corresponding critical ratios (t=diff./S.E.diff.) are given. It is to be noticed that the red-green blind are on the average about 9.6 times as weak in red, 12.9 times as weak in green, 1.17 times as weak in yellow and 1.87 times as weak in blue as the " normal " group. Of the differences shown in the table, those for red, green and blue are definitely significant, while the difference for yellow is not significant.

These data are very interesting, for they show that red and green are very greatly weakened for the colour blind, while blue is slightly weakened and yellow is not changed by the great reduction in red-green sensitivity.

Another interesting group of differences between colour weaknesses is given in Table 19. Here the eleven deuteranopes who did the rotating disks experiment are compared with the eight protanopes, using Student's method for estimating the standard errors of the differences of small samples. The differences in colour weakness for red between deuteranopes and protanopes are not significant, nor

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TABLE 19

COMPARISON OF DEUTERANOPES AND PROTANOPES FOR RED AND GREEN
WEAKNESSES IN THE ROTATING DISKS TEST

	Groups or Colours Compared	Difference of means	Estimated S.E. diff.	t
RED	8 Protanopes and 11 Deuteranopes	25°	28·5°	0·88
GREEN ..	8 Protanopes and 11 Deuteranopes	43°	15·8°	2·72
11 DEUTERANOPES	Red and Green	52°	19·3°	2·69
8 PROTANOPES	Red and Green	16°	27·6°	0·58

are those for protanopes between red and green.   The differences
between deuteranopes and protanopes for green, and for deuteranopes
between red and green, however, are significant on a lenient level
of probability between 2% and 1%. This means that there is a
probable tendency for deuteranopes to have more difficulty in
distinguishing green than red from yellow of equal brightness, and
to be weaker in green than protanopes. On the other hand it is clear
that protanopes do not, in this group, have more difficulty in dis-
tinguishing red than green from yellow of equal brightness, and are
not more weak in red than deuteranopes. The asymmetrical character
of this conclusion is interesting, but at present no interpretation can
be offered.

BEARING OF RESULTS ON COLOUR-VISION THEORIES

For the problem of colour-vision theories the absence of correla-
tions between colour weaknesses and brightness levels among the
colour blind is very interesting. For example, according to the Young-
Helmholtz theory, subjects who are sufficiently weak in red and
green or in either of these colours to be called colour blind should
show a corresponding diminution in sensitivity to yellow, and there
should be a strong positive correlation between red and yellow or
green and yellow weaknesses. This is not found among normal
subjects, but it might be said that the colour weaknesses in them are
so small that their effect might be masked by random errors and the
correlations reduced in this way. In red-green blind subjects the
colour weaknesses are so great that random errors could not possibly

be sufficiently large to make any difference. Similarly, on the Young-Helmholtz theory there is no source of brightness other than by the combination of colours, and any marked diminution of sensitivity to one or more of the three primaries must effect the brightness level of polychromatic combinations and especially yellows, accordingly. Marked positive correlations between brightness levels and colour weaknesses must be expected, because the Young-Helmholtz theory provides no way in which saturation may be lost and brightness remain unaffected. Since the colour-blind subjects are red-green and not yellow-blue defective, and since their red-green weaknesses are very great, we should expect at least that the correlations of red and green weaknesses respectively with brightness levels would be large enough to outweigh random errors, though yellow-blue weaknesses would not give greater correlations with brightness levels than for normal subjects. This expectation is not fulfilled. All the correlations are small, statistically not significant and there are no marked differences between the red and green correlations with brightness levels and the parallel yellow and blue correlations. In other words, the enormous weaknesses in red and green in the colour blind do not have any effect on the brightness level of combinations at the mid matching point, although, of course, in protanopes the red end of the spectrum is markedly darkened. Therefore a colour-vision theory must be able to provide explanations of two different circumstances; saturation of red and green may be almost completely lost, either with or without corresponding loss of brightness. The objection might be raised to the argument put forward above, that the loss of sensitivity in red-green blindness must affect the standard desaturated yellow used to determine the brightness of the red-green mixture, and make it less bright accordingly. Since greyish yellow is much more polychromatic than the red-green mixture, the effect on it would be expected to be less than on this mixture. Such an effect would be in the same direction on both, however, and ought to give a high positive correlation on the Young-Helmholtz theory.

An interesting variant of the Young-Helmholtz theory, due to Fick, and explained by Walls,[1] is intended to meet this difficulty. If we assume that colour blindness is due to diminution in sensitivity or, in extreme cases, to absence of one of the three photochemical substances, then it is impossible to understand how yellow comes to replace both the red and green sensations in colour blindness (at least of the deuteranope), or to understand how saturation may be lost and brightness retained. To meet these difficulties Fick suggested

that we might suppose that the curve of red sensitivity could be shifted to coincide with the green curve until they were super-imposed. There are corresponding possibilities for the green and violet curves. The possible shifts of the violet curve need not be discussed at the moment, since we are dealing with red-green blindness.   It is claimed that, if the red curve is shifted to coincide with the green curve, we have the protanope, with shortened red end of the spectrum and only two sensations : yellow (red+green) and blue. If, on the other hand, the green curve is shifted to coincide with the red curve, we have the deuteranope, with normal spectrum and no sensations but yellow and blue. Any number of intermediate conditions are readily imagined.   In order to make this theory possible we are forced to suppose that each of the three curves of sensitivity stretches almost to the ends of the spectrum; that red alone is excited between 750 and 650 mμ, while between 650 and 430 mμ all three sensitivities are excited, and violet alone from 430 to 390 mμ.   These three curves must overlap in such a way that they are not statistically separable, otherwise we should have three peaks of intensity (and saturation), which are not found in the spectrum.   There must, on this scheme, be an enormous desaturation with white for all colours between red and violet, and a rapidly increasing brightness towards yellow-green, after which it should decrease again.   These two conditions accord reasonably well with the characteristics of the visible spectrum.   Colour can be experienced, on this theory, only when any individual curve, or two curves taken together, overtop the three taken together : it is the difference between the complex excitation at a given wave length which makes up white or grey and the total excitation at that point.   Neither blue nor yellow can be a pure sensation : yellow is red+green+white; and blue is violet+green.

As far as red and green are concerned, on this theory, decrease in ability to distinguish between either of these colours and yellow must occur at the same time and to the same extent. The theory could not be supported unless there was a very high correlation between red and green weaknesses in the colour blind, whether it is the red curve or the green curve that is shifted. Yellow, however, could never vary while red and green were unaffected, unless every change in the yellow sensation were correlated with a change in violet owing to a shifting of the violet curve which would be the supposed explanation of tritanopia. If yellow varied in this way there would always be a high correlation between yellow and blue weaknesses, and this has not been found. There is a further difficulty, that in

extreme deuteranopes, at least, it would be inevitable that the green part of the spectrum should be darkened somewhat, on account of the reduction in the height of the combined curves at the green part, as the green curve moved towards the red. Darkened green is an extreme rarity in the colour blind, however. Finally, on this theory it would never be possible to account for the distinction between variations of range and variations of deviation, or to show how the two types of variation could be irregularly combined. It could not account for the distinction between the colour blind and the anomalous, and this distinction is of fundamental importance. To meet some of these objections to Fick's theory, we might suggest a change, namely, that in protanopes the red curve is shifted towards the green curve, but that in deuteranopes the green curve is not shifted but simply elongated towards the red. This, again, would not enable us to account for the difference between ranges and deviations, or between the anomalous and the colour blind. Further problems would be raised if we attempted to account for marked red weakness (not sufficient to be called colour blindness) without any darkening of the red.

In a similar way, there are difficulties for the Hering theory in its original form. Red and green are opposites, and so are yellow and blue. The diminution of the member of each pair which is weakened in colour blindness might be balanced by relative increase in the other member, unless we can assume that both anabolism and katabolism could occur together, which would appear to be impossible. On this theory, however, colour blindness is generally supposed to be due to loss or weakening of the balanced reactions in pairs. In red-green blindness the reactions of katabolism to red and of anabolism to green are both diminished in intensity, so that the sensitivity to both colours is reduced and the threshold for the distinction between them is greatly increased, or the reactions may be lost altogether and neither red nor green can be seen at all, while brightness will be very little diminished and yellow and blue left unimpaired. In yellow-blue blindness it will be these colours which are diminished or lost and red and green will be unchanged, while brightness again will be very little reduced. Presumably both conditions might occur together. On this theory there should be large positive correlations between red and green and between blue and yellow weaknesses, little or no correlation between colour weaknesses and brightness levels, and none between other pairs, such as red and yellow or green and blue. Since we do not, in this experiment, find the expected correlations between red and green or between

yellow and blue weaknesses, either in the colour blind or in the normal subjects, it cannot be said to support Hering's theory in its old form. The lack of correlation between colour weakness and brightness level, however, does accord with expectations based on the Hering theory.

On this theory there is no explanation for the difference between deviations and ranges in either the red-green or the yellow-blue colour pairs. We might suppose, however, that the point of balance could be moved to one or other side, in addition to the loss of sensitivity or independently of it. This is the modification of the original Hering theory which Houstoun's scheme provides for, and on his view we should expect either much independent variation in sensitivity to the two colours in each pair, or even a tendency for the paired colours to vary in opposite directions, giving negative correlations between colour weaknesses. Positive correlations would be expected if weaknesses were relatively greater in their effect than the displacement of the point of balance, and negative correlations where displacement was relatively greater in effect than loss of response. Absence of correlations would be expected quite reasonably where the effect of displacement or deviation counterbalanced the effect of increase of range or threshold. Such a theory accords much more closely with the observed facts than any other.

On Ladd-Franklin's theory red and green sensations were evolved by being split off from yellow, and yellow and blue were evolved by being split off from grey. Red and green weaknesses will be explained as the result of reduction in the completeness of this splitting, and similarly for yellow and blue. It would not be possible for red and green to be weakened separately from each other, nor for yellow and blue, and it would not be possible for yellow and blue to be weak until red and green sensations had been lost. These expectations are not in the least supported by any of the data available from the present experiment. To support her theory it would be necessary for red and green weaknesses to be completely correlated, both in normal and colour-blind subjects, and the same for yellow and blue. Since we could not find any subjects (on her theory) who were weak in yellow and blue without being red-green weak too, all colours would be expected to show strong positive correlations if there was any measureable weakness at all. Her theory does not meet the difficulty of the distinction between range and deviation at all. On the other hand the problem of brightness levels is less serious on her theory than on the Young-Helmholtz theory, because, on her theory black, grey and white would be retained effectively as distinct

sensations even when all differential colour sensitivity were lost, hence absence of correlation between brightness level and colour weakness accords with her view.

In this chapter we are dealing especially with the peculiar weakness of the red-green blind, which, on Edridge-Green's theory, is the inability to distinguish between red and green at the dichromic level, and/or between red and yellow and yellow and green at the trichromic level, since the colour blind are either dichromics or trichromics (not trichromatics) on his theory. He must have been aware that on his theory in its strict form the limiting colour sensations must be red and violet, but he accepts the fact that the colour vision of most dichromics appears to be much more like yellow and blue than red and violet. This difficulty may be purely a question of the use of colour names. At any rate, on his theory red-green blindness must result from a simultaneous loss of red and green and/ or red, green and yellow. The dichromics are the completely red-green blind, and the trichromics are the incompletely red-green blind of Ishihara's classification. On Edridge-Green's theory strong positive correlations would be expected between red and green weaknesses. If we assume what seems most probable on his theory, that the remaining sensations of the dichromics are blue and yellow rather than red and violet, then yellow-blue weaknesses would not be expected except when the distinction between red and green had been completely lost, and this expectation is not fulfilled. It was clear that, with the exceptions of the familiar darkened red vision of the protanope, and darkened violet, which he mentions, Edridge-Green realised that loss of differential sensations for colour left the brightness levels of the corresponding parts of the spectrum unaffected. This would accord with the absence of correlations between colour weaknesses and brightness levels.

Taking all these facts and problems into account, it may be said that the Young-Helmholtz theory would be the most difficult of all colour theories to support, Edridge-Green's and Ladd-Franklin's would come next in difficulty, and then Hering's. A modified form of the latter would seem most likely to afford us an efficient working hypothesis.

General Effect of Colour-Vision Weaknesses

It will be worth pausing here to make a general analysis of the effect of colour-vision weaknesses, based on the data studied, so that the problems to be faced in the remainder of the book may be seen

in clear perspective. Red-green blindness is a drastic reduction in sensitivity to distinctions between red and green, red and yellow, and yellow and green, so that these distinctions can be made either not at all or only when the contrasts of saturation or brightness of the colours are perhaps ten or twenty times as great as required by normal people. In yellow-blue defects the difficulty lies in distinguishing between yellow and whitish grey, between blue and darkish grey, hence in some cases between yellow and blue, unless contrasts of saturation and brightness are much greater than normally required. Parsons[2] has pointed out clearly that colour blindness is a reduction defect: colour-blind people see fewer gradations or distinctions of hue and saturation than the normal, or see them with much greater difficulty. He reaffirms what has been said before, that colour-blind people will accept colour matches made by the normal, but can make numerous matches which the normal will reject. We are therefore in a position to measure their weaknesses in terms of their differential thresholds for suitably arranged colour matches, which are found to reveal their weaknesses clearly; this is what has been done in the present experiment.

There are important exceptions to Parson's generalisation about the colour matches made by colour blind and normal people, as he realises, and these exceptions are the anomalous and deviant subjects whose thresholds are not much greater than normal, but who reject certain normally accepted colour matches and insist on making others which are normally rejected, but are accepted by many colour-blind subjects. The anomalous subjects (but not the deviants) are failed by tests such as the Ishihara Test or Stilling's Tables, and are dangerous in certain situations where red and green signal lights are used.

Strangely enough, many colour-blind people, and almost all the anomalous, are not aware of their defect until tested, when they are surprised and often distressed. Some do not admit the defect even when numerous tests have been carried out and the normal performance on these tests has been demonstrated to them carefully. They may still think the tests are in error, that the tester is deceiving himself, or they may say they are colour blind in the tests but not in daily life. On the other hand the majority know only too well of their failings and will welcome an opportunity to spend an hour in the Laboratory where the nature and extent of the defect can be accurately and sympathetically explained to them. The only efficient way of demonstrating the nature and magnitude of their defect to the colour blind is to show them the rotating disks (or a similar

experiment), and tell them that the normal can distinguish the red and green as clearly and with as much confidence as they can distinguish the yellow and blue. Then, supposing that red is yellow and green is blue, to show their red-green range and deviation in terms of the yellow-blue disks. They are almost incredulous.

It may seem odd that a man who cannot distinguish red from green, unless he has secondary guides not directly connected with colour, should think his colour vision normal, but he has never seen the difference between these colours as we see it, and there is no possible way of enabling him to have this experience. Even the method just described, of pretending that red is yellow and green is blue, completely lacks the concreteness of real experience. The red-green blind very naturally may suppose that we see no greater differences than he sees, but are much more clever at making distinctions which he finds difficult or impossible. He may think that when he was a child he failed to learn to use correctly and efficiently the names of what are to him the closely similar tones and shades of red and green. Since there may be also certain hues between green and blue, and between blue and red for which he has a difficulty in finding suitable names in the language, he may think he sees colours which normal people do not see and which are therefore nameless, though in fact some of them will prove to be indistinguishable from grey to him when efficiently tested.

In order to understand more fully the difficulty which a colour blind person has in appreciating the nature of his own weakness, we could take the following example, bearing in mind always that the colour blind has no possible way of realising the magnitude of many colour differences we see easily. The ordinary person may find it difficult to be confident of contrasting accurately such pairs or terms as reseda and olive green, cerise and cherry, petunia and magenta, or elephant grey and pearl grey. As Edridge-Green pointed out clearly, the difficulty is greater when the name must be applied correctly to a single spot or patch of colour, without the help of a standard, and is less when the names can be applied differentially to two spots, for example, that one is reseda and the other olive. The normal person, unless he has had much practice, may feel that there is an unnecessary multiplicity of names and that their use depends on making hair-splitting distinctions, as between cerise and cherry, and he may doubt that the distinctions are consistently upheld. A red-green blind person may feel just the same difficulty in employing efficiently and consistently such pairs of terms as light red and grass green, sky blue and magenta, scarlet and orange,

blue and violet. He thinks the colours to which other people seem to be able to apply these terms differentially are very much alike, and he may doubt that we are really consistent about making distinctions so subtle (to him). He may think it is just a little conceited on our part to be so " slick " about the use of confusing terms like red and green. Consequently it is easy for him to suppose that there is really nothing wrong with his colour vision, but that the ordinary man is trying to be over-subtle. He may think most of us are deceiving ourselves, and that, since he does not pretend to do the impossible, he is the one really sincere and honest person among a population who pretend, for example, that the sky should be called " blue " while the rose is " pink ", although there is no real difference between them.

Colour blindness is a highly variable defect. Even the researches of Edridge-Green,[3] Houstoun[4] and Collins,[5] and their fascinating descriptions, do not convey clearly to everyone the greatness of its variability. If we succeed in finding two colour-blind people who have exactly the same degrees of defect, measured by accurate tests, which is unlikely, we should still find that their reactions to colours in daily life were completely different; this will be made clearer in the sequel. Head[6] has shown in his brilliant researches on aphasia and kindred disorders of speech caused by brain injuries, that the defects manifested in thinking, speaking, reading and other activities are always peculiar symptom-formations, uniquely belonging to the individual concerned. They are not so much the direct products of certain mechanical destructions of tissue, as they are the outcome of the individual's own efforts to overcome those effects. They are the combined product of his efforts to adapt himself on the one hand and the direct effect of the cerebral injury on the other. In the same way the colour vision of a colour-blind person is not a rigidly mechanical product of exact visual limitations, but is also due to his efforts to overcome certain difficulties he has always met with, and the total result in daily life is a unique construction depending on the individual's personality, interests and mode of life. Reciprocally, his personality, interests and way of life will have been influenced by his colour difficulties. It is wholly unscientific to think of colour blindness as if it were merely a mechanical fault, like a sparking plug with too wide a gap. To be able to measure the fault must not lead us to the error of forgetting its many psychological repercussions and its influences on the personality as a whole. This is as true of all visual defects as it is of colour blindness.

One colour-blind person disclaims all knowledge of colours or

interest in them in daily life, another claims that his colour vision is normal and disputes the validity of the tests. There are numerous complications of attitude almost too subtle to explain. Facility in the use of words as colour names in appropriate settings is often so great that a man does not realise that he fails to see a colour, except when he fails to use a name correctly, and then he may think it was just an error of terms. In this way the distinction between sensation and perception is admirably illustrated by some defective subjects. Since a man knows that all pillar boxes are red he has no difficulty in naming the colour of pillar boxes and actually perceives them as if red. If by chance he was confronted with a pillar box which had been painted black for the purpose of testing him, he would see it as red too, and call its colour by the wrong name. In order to avoid the influence of naming, it is absolutely essential to use test objects whose character, size, shape, use or familiar associations provide no clue to their colour. Just as the blind man has become a master in directing his activities by sound, and gains the reputation of having exceptionally acute hearing, so the colour-blind man may become a master at distinguishing colours by differences of the shape, size, names and uses of coloured objects, and by the brightness and surface appearance of their colours. Dyes affect differently the objects they colour, and one may learn to distinguish black from red wool by the feel or the general appearance of the yarn. One colour-blind man could see that tramcars in Paisley Road were green, and those in Hyndland Road yellow, but if a yellow car went along Paisley Road he thought it was green. He was a deuteranope. Similarly, a protanope saw cars as red on the Milngavie Road, but blue on the way to Rutherglen. Perception depended on the individuals' expectation based on the colour name generally applied by other people to cars allocated to a particular route in Glasgow.

The extent and manner in which these secondary constructions of perception and behaviour are built up in the individual's life are almost infinitely variable. One man remains at the level of constantly suspecting himself of some weakness where colours are concerned, and watches his companions, almost unintentionally, to note any frown or other indication that he may utilise to correct a possible error, while another has developed a whole system to protect himself from noticing or thinking that he has a weakness. The colour blind habitually trade on doubt, obtaining a decisive response from their companions frequently as a result of their own slight hesitation, which may look almost normal; and then they may believe that they

decided for themselves and their companions may have that impression too. A good illustration of the way in which secondary cues may operate in perceptions is that of a colour-blind woman who was doing the Ishihara Test. She absolutely failed to see a pink and salmon figure " 2 " on a blueish and greenish background until it was outlined for her with the butt end of a pencil, leaving no mark. Then she saw it clearly for a minute before it faded again. This is a most instructive experiment, which I have done with a number of colour-blind persons. If the word " Two " had been whispered instead of outlining the figure, it would have had the same effect, and she would have perceived for a moment the figure named.

All these points apply, as every psychologist knows, not only where there is gross diminution of sensitivity, but also to normal perception. Thus ordinary perception in all fields of apprehension is constructed out of the combined influence of many sensory cues which are inter-related with infinite and varied complexity, and colour blindness only provides extreme examples. The effect of related sensory cues was sometimes seen in a clear and interesting way in the rotating disks experiment. The five differently coloured papers, red, green, yellow, black and white, employed in the red-green test, were not identical in surface texture any more than skeins of differently coloured wools are identical apart from colour differences. Consequently the disk composed of red and green sectors had a very slightly different surface texture from the one composed of yellow, black and white, for at least some of the subjects, even when the rate of rotation was so high that there was not the least suspicion of flicker and the two disks looked perfectly smooth and uniform. This difference of texture was sometimes apparent when there was no colour difference. Normal subjects occasionally pointed it out, or simply ignored it. Colour-blind subjects, however, who never miss an opportunity to exploit differences of surface texture as possible guides to colour differences, sometimes interpreted the slight difference of texture as a colour difference which they could not name. One such subject insisted that the colours of the two disks were " totally different " at the normal matching point, though he was later found to have a very large range including that point. By using colour filters in later experiments this difficulty of texture has been overcome.

The use of words is frequently deceptive in perception and also in thinking, if we look at it in a certain way. It is well known that facility in the use of technical terms, for instance, easily conveys the impression of real knowledge and insight, not only to the listener,

often somewhat puzzled, but also to the speaker himself, who, like the colour-blind man, may have the impression that his efficient use of terms must imply knowledge as perfect as that of the expert, who uses the same words in almost th esame ways. Thus the man who can call the fruit trees in his garden correctly by name assumes, like his admiring friends, that he has expert knowledge, just as the red-green blind man who has learned to call pillar boxes red assumes, and may genuinely believe, that he can see their colour as clearly as any person who calls them red because he has learned to apply the term red to the colour rather than to the pillar box.

GENERAL NATURE OF THE DEFECTS

In order to understand red-green blindness we must think of the browns, fawns, olives and colours made by desaturating oranges, yellows and yellow-greens, as if they invaded red on the one hand and green on the other. This invasion occurs in a highly variable manner, so that no two colour-blind persons are exactly alike. In the same way blue tends to invade violet and purple on the one hand and blue-green on the other. Thus there is a varying tendency for colour-blind people to see only two colours—yellow and blue—but I agree with Collins[7] that they are seldom if ever strictly dichromatic. To prove true dichromacy would be very difficult, because there are usually slight differences of saturation even where no differences of hue exist, and the person often has a considerable margin of uncertainty about these saturations. The most common difference is that red tends to be a rather more saturated, and green a rather less saturated yellow. On the whole the tendency is for red to fade away before the invasion by orange and yellow; green before the invasion by yellow-green and yellow; violet on the one hand and blue-green on the other to fade before the invasion by blue. Even in the most extreme cases there may still be the difference between red and green mentioned above, and a similar difference between violet and blue-green. Violet tends to be a rather saturated blue and blue-green more greyish. The exact points at which difference of saturation remains and difference of hue has vanished is very difficult to determine. There is no rigid margin between hue and saturation, but a flexible and individually variable threshold, of the kind with which psychologists are familiar in other fields.

Edridge-Green[8] has pointed out that certain red-green blind subjects may see a colour which they call " reddish-green ". This must not be taken to mean that they see both the qualities of red

and green as we see them but combined in one hue. No doubt the reddishness is more like what we should call orange or even merely yellowish brown, and the greenishness is more like our olive or a desaturated yellow. Hence a colour to which we should apply the name fawn may to the colour blind appear to combine the qualities he would call red and green, just as a purple may appear to us to combine qualities we should call red and blue. Then he may use the term " reddish-green " with fair frequency, as shown by Collins,[9] and it is no more difficult to understand from his point of view than the term " reddish-blue " for ourselves. At a further stage of red-green defect the possibility of a reddish-green hue is lost and only differences of saturation remain. Fawn is then identified with green as the colour blind sees it, if little saturated, and with red as he sees it, if the saturation is greater. Indeed in this way the colour blind may learn to make many correct discriminations by saturation when we should employ hue as our guide. In addition to reds, fawns and greens there may be yellows, often correctly distinguished by him because of their greater brightness, since most familiar yellows are much more intense than reds and greens. The familiar traffic lights, for instance, may be easy to distinguish for a red-green blind subject : the red is relatively more saturated, the green relatively less so, and the yellow is much brighter, because most yellow filters transmit much more light than red or green ones, quite apart from the greater luminosity of yellow rays. The colour blind may think we are simply more clever at making these same distinctions, or that what we call " red " is simply a yellow more saturated to us than it is to him, though still yellow in hue. If presented with a series of coloured papers, reds, oranges, yellows and greens, and asked to separate them into their colours, a man will say of one paper, " That's a red ", of another, " That's a green," " That's a yellow ", and so on. When asked to explain exactly what qualities lead to his making these perfectly correct distinctions he will assure me that there is absolutely no difference in colour, but that " a red " is not at all like " a green ". It must be remembered, however, that colour blindness is a highly variable defect, and no generalisation can be made for which some exception will not be found. The important distinction between protanopes and deuteranopes will not be dealt with here.

The characteristic tendency for yellows to invade red on the one hand and green on the other in the red-green blind, appears in a greatly diminished form in the red-green colour-weak subjects. It is not a characteristic of the anomalous or of the deviant classes. In the same way, in the yellow-blue weak subjects there is a tendency for

greys to invade yellow on the one hand and blue on the other, making them less saturated and reducing the sharpness of the distinction between them. This, again, does not apply to the yellow-blue deviants. In yellow-blue blindness the invasion of greys into the blue and yellow directions is greatly magnified as compared with that in the yellow-blue weak, so that there is a range of desaturated blues and yellows which cannot be distinguished from greys of the same brightness. If blue or yellow is to be seen, then it must be sufficiently saturated to fall outside the threshold of this range of greys. This is exactly comparable to the condition in red-green blindness, if the terms grey, yellow and blue are exchanged for yellow, red and green respectively : yellow-blue weakness is not a condition specifically affecting violet or blue, and cannot be defined as violet or blue weakness (or blindness). There is, however, a darkening of the violet end of the spectrum in some blue-yellow weak subjects, which is comparable with the darkened red of the protanopes. This darkening of the violet was mentioned by Edridge-Green in 1891,[10] but has not been commonly recognised. Thus as we approach blue-yellow blindness there is a tendency for colour vision to be reduced towards red-green vision, just as in red-green blindness it tends to be limited to yellow and blue. Unfortunately few students of colour vision have had the opportunity of studying even a single person sufficiently weak in yellow and blue to be called blue-yellow blind. Hence we are not in a position to make more than tentative claims.

Blue-yellow weak subjects are often aware of the presence of some defect, and, if they are thoughtful persons, they may have been puzzled that they can pass the ordinary tests of red-green blindness and yet have special kinds of difficulty with colours. Two of my subjects were in this position, and will be described in another chapter. As there are many stories about red-green blindness, and few about yellow-blue defects, I shall add here one which was told me by a yellow-blue weak subject in this experiment, when asked if he knew that he had any such weakness before he was tested. He said he was one day visiting a dye-works on business and, while waiting for his appointment, he was asked by a foreman whether he could distinguish any difference between a certain bale of yellow cloth and a number of others beside it. After a prolonged examination and asking for an improvement in the lighting, he said that he could not. The foreman then told him that the bale was one which had been returned from China because it did not match the standard yellow, and that the others did match the standard. Even then he could see no difference.

Colour Naming by Defectives

Many people have thought that the colour blind were illogical in their use of colour names, or used them wholly at random, but I agree with Collins[11] that their use of these names is quite consistent within the limits of their own experience. Since the extent and character of the defects is very variable, even within the two main classes of deuteranopes and protanopes, all colour-blind subjects cannot be expected to use the same colour names in the same though abnormal ways. In talking to a colour-blind subject, unless we have some special knowledge of the exact nature of his defects, we cannot foretell in what particular ways he would be expected to use colour names, so we might have the impression that the colour naming of these people is random and unsystematic. This impression will in practice be emphasised by what has been pointed out above, that colour-blind subjects vary greatly in the extent to which they have compensated for their defects in secondary ways.

In order to understand the names used by the colour blind we have to think of the colour circle, divided into four quadrants, with red, yellow, green and blue at the divisions and the intermediate colours between. If a man has extreme weakness in sensitivity to red and green, as we pass from blue, for which he may have normal sensitivity, through violet, purple, magenta and carmine to red, the only change noticeable to him may be a steady diminution in blueness, and he will call violet and purple " blue ", magenta " sky blue ", carmine " pale blue ", and a real pale blue may be indistinguishable from rose pink. If his defect is less extreme and he has compensated for it sufficiently, he may have learned to call magenta and carmine " red ", and so proceeds from blue to red, but the intermediate purples are not subject to such subtle distinctions for him as we make as a matter of course. If he is sufficiently defective there may be a colourless region in the purples or magentas, but by the time we reach red we shall find that he sees a more saturated colour distinct from blue and identified with yellow by the greater, and distinguished from it as " red " or " pink " by the lesser defectives. As we pass from red to yellow for the colour blind there may be no change except a gradual loss of saturation, a change which proceeds in the same way from yellow to green, and such a person may wonder why we call a certain yellow " orange " and another " yellow-green ". A less seriously defective subject may see a fairly distinct difference between saturated red and saturated green, and will have less difficulty in fitting in " yellow " as an intermediate colour, but may still

be puzzled over orange and yellow-green. As we pass from green back towards blue for the very colour-blind person who is still normally sensitive to blue, this may be equivalent to a change from pale yellow to blue, or from near grey to blue, and no hue can be found to which a separate term blue-green can be applied. Thus, in general, for the colour blind all distinctions between yellows and blues will correspond to the distinctions implied by our terminology for those colours, while reds and greens approximate towards yellows, except for the protanopes, for whom red is greatly darkened. All such names as violet, purple, carmine, orange, yellow-green, peacock blue-green, seem unnecessary. As a result, there are often two or more names, such as purple and blue, rose and pale blue, orange and yellow, peacock and blue, which correspond to the same colours for them. The so-called confusion in the use of colour names by the colour blind arises from their efforts to employ too many names for the number of distinguishable hues and saturations they see. Their errors in naming are due to the multiplicity of names, not to anything illogical on their part.

With the yellow-blue blind and even with the yellow-blue weak either or both blue and yellow are diminished in saturation compared with the normal. Dark grey tends to invade blue and light grey or white tends to invade yellow. The intermediate colours, violet and blue-green tend to join hands across the blue, while orange and yellow-green may tend to join across yellow. Thus there may be difficulty in accepting distinctions made by the normal person about any of the four intermediate colours : blue-green, violet, orange and yellow-green. The yellow-blue weak person will often be able to report having had disputes or differences of opinion about why a blue-green should not be called " green ", why brick red should be distinguished from orange, and so on. He may, like one of my subjects, say that he often confuses yellow with white, and he may call orange beads " yellow " and yellow ones " white ". Later it will be shown that the most marked characteristic of the blue-weak is to see desaturated blue-greens, like Cambridge blue, as " green " and to refuse to call them blue.

THE ISHIHARA TEST FOR COLOUR BLINDNESS

In a very interesting letter to *Nature* Vernon and Straker[12] showed that the percentage of red-green defectives in the population of Great Britain varied from 5.37% to 9.45%, with an average of 7.49%. These figures were found in the course of testing recruits

for the Royal Navy in 1942 and 1943. This was an unexpected result, since the figure usually accepted has been about 4% or 5%. These authors suggest that the difference is due to the difficulty of the test used, which was a modified form of the Ishihara and Stilling's Tables combined. They think it picked out many of the " colour-weak " or " anomalous trichromats ", as well as the strictly colour blind.

In the rotating disks experiment about 4% of red-green blind subjects were found, and 2% of green anomalous, purely by chance, in the 109 men tested. It is not easy to be perfectly confident of the absolutely chance discovery of colour-blind men under the conditions of this experiment. With many it is almost impossible to avoid suspecting that they are colour blind before they are asked to do the tests, and at the same time it is extremely difficult to avoid the escape of a certain number of colour-vision defectives, who are asked wholly at random, but refuse to be tested for a variety of personal reasons, some of which it is impossible not to take seriously. For more than a year I tried to get one man who was asked purely at random to come to the laboratory, but he was always too busy for that, although he was quite willing to sit over a cup of coffee to chat for as long as it would take to do the tests, but if this was pointed out to him, he invariably had a train to catch or important work to do. This was specially annoying because his curious prevarication when asked to name the colour of some green curtains raised serious suspicions that he might be colour blind. Another man has repeatedly asked to be tested, implying that there was little doubt that his colour vision would be found to be abnormal, but has invariably failed to keep the appointments that were made. In testing for the Royal Navy it is more likely that the proportions of red-green blind would be less rather than greater than the true proportions in the population, because a certain number who knew their defects would be sure of detection would refrain from choosing the Navy as their branch of service.

Many of the subjects in the rotating disks experiment were asked to do the Ishihara Test. At first it was hoped that the degree of colour weakness might be revealed by the number of mistakes, alternative or doubtful readings in the test, and that there might be a correlation between the two tests. This hope was altogether abandoned after a more careful study of the real nature of the problems and a review of the results obtained. The Ishihara Test was used with a standard 60-watt lamp fitted with a half-watt-to-daylight colour filter, and the distance of the lamp was about one metre. It was placed in such a position that the subject could not take advan-

tage of the differential reflection of light from the various coloured inks in the Ishihara Test. This is a very important point when using this test either in daylight or in artificial light; many colour-blind subjects can read figures which " shine " in a certain light, while normal subjects can read the alternative figures for colour-blind subjects in the same way. The " daylight " filter converts half-watt light to normal daylight, and is much more constant than even the light from a north window. The test plates were in the dark when not in use, and were thoroughly clean, and the subjects were tested with great care. Tables 20 and 21 show the results for 14 men and

TABLE 20

PERFORMANCE OF MEN IN THE ISHIHARA TEST

Reading		Correct	Double	Errors	No Reading
Protan-opes	Extreme (3)	1, 2, 1	0, 0, 1	9, 15, 16	15, 8, 7
	Moderate (3)	1, 2, 2	2, 1, 3	11, 11, 13	11, 11, 7
Deuter-anopes	Extreme (3)	1, 1, 2	2, 1, 1	15, 15, 15	7, 8, 7
	Moderate (5)	1, 1, 1, 1, 1	3, 4, 3, 3, 4	13, 12, 12, 13, 12	8, 8, 9, 8, 8
Anom. Green	(2)	2, 2	8, 2	9, 13	6, 8
R-G Weak	(13)	Mode 21 Scatter 14—24	1 0—7	4 0—4	0 0—1
Normal	(9)	Mode 20 Scatter 14—24	2 0—8	2 1—4	0 0—5

4 women who were red-green blind, 2 green anomalous men, 13 men and 18 women who were red-green weak, and 9 men and 27 women who were normal. The red-green weak were those with more than twice the modal range in the red-green test. A distinction was made between moderately and extremely red-green blind, in terms of their ranges of matching. The distinction between the anomalous and the red-green blind has been explained earlier in the chapter.

In these tables the numbers of correct readings of single plates in the Ishihara Test are shown for the colour blind, and anomalous subjects individually. For the colour weak and normal subjects the

TABLE 21

PERFORMANCE OF WOMEN IN THE ISHIHARA TEST

Reading		Correct	Double	Errors	No Reading
Protan- opes	Moderate (2)	2, 1	5, 4	11, 12	7, 8
Deuter- anopes	Extreme (1)	1	0	16	8
	Moderate (1)	2	6	11	6
R-G Weak	(18)	Mode 22 Scatter 15—25	0 0—7	4 0—7	0 0—1
Normal	(27)	Mode 21 Scatter 16—25	0 0—6	3 0—6	0 0—1

modal frequencies of correct readings and their scatter are shown. The frequencies of double readings, unqualified errors and complete failures are shown in similar ways. A perfect reading of the test requires twenty-five correct interpretations, including no reading of each of four plates which are supposed to be illegible to the normal. A complete failure requires correct reading of the first plate, which is used to show the subject what he is expected to be able to do, eight plates with no reading and sixteen simple errors including the four plates illegible to the normal. No double readings or alternatives should be given by anybody if the test is perfectly satisfactory.

The tables show that the Ishihara Test successfully failed all the colour blind and anomalous subjects, even on a level so lenient as two correct readings in twenty-five (one of which was the "joker").[13] The two anomalous subjects were not distinguished at all by the test, and this result has been confirmed with many more green anomalous and three red anomalous subjects since the rotating disks test was done. It is clear that the Ishihara Test would fail a considerable number of normal and red-green weak subjects if the standard of failure were as strict as 14—18 correct readings, but the number of correct, alternative, faulty and blank readings gave no accurate information of the degree of the subjects' weaknesses. It is quite unknown whether any of these subjects might be dangerous in practical situations, as, for instance, in the Navy, and ought to be failed in a strict examination for colour vision, but if they are to be failed, then the Ishihara Test could not be used to discriminate them from

the perfectly normal. If the test was used with variable lighting, such as ordinary daylight, and if the plates were as soiled and faded as some recruits have told me they are, where large numbers have been tested, or if the testing was in the hands of those who do not have serious laboratory experience, then it will be even less reliable. Indeed, variations in quality of daylight from N.E. to S.W. might account for the frequency differences reported by Vernon and Straker. In the British printing of the Ishihara test, the composition of the lights reflected by the inks are not always the same as in the Japanese printing, though the colours are almost the same, and this would be another possible source of errors.

A proportion of the red-green weak and normal subjects who made about the modal range of errors in the Ishihara Test were yellow-blue weak, and for a time it was thought that yellow-blue weakness might have an effect on the results with this test. They were not the ones who made the greatest number of errors, and yellow-blue weakness cannot be the main reason for their mistakes. Special cleverness of certain subjects, who had very good colour vision, and who could quickly pick out the figures they are not supposed to see, as well as the correct figures, was a frequent cause of as many as 4—8 mistakes and/or double readings, and some subjects with particularly good colour vision have given four or more alternative readings for a single plate. This shows imagination and quickness at the spatial integration of dot patterns rather than colour weakness. Another source of errors was anxiety, especially where the subject was worried about his vision, and in one subject an inability to converge the two eyes accurately caused her to fail in the Ishihara Test, but it was known that she had this difficulty in ordinary reading as well and had no colour weakness.

Vernon and Straker were therefore probably correct in their supposition that the Ishihara-Stilling Test used in the Navy picked out many "colour-weak or anomalous trichromats" as well as the strictly colour blind in the research they reported. These Pseudo-Isochromatic Tables, however, though satisfactory for detecting the colour blind, are far too unreliable for any attempt at picking out those with small colour weaknesses because the number of errors made is no indication of the degree of colour weakness. If anything the Ishihara Test is worse than Stilling's Tables, because of the numerous alternative readings, which, though intriguing, are dangerous in a serious test.

Before leaving this subject it might be useful to comment on Vernon and Straker's terms "colour-weak" and "anomalous

trichromat ". Their use of these terms would suggest that the colour weak and the anomalous trichromats are identified, or perhaps that the anomalous trichromat is the more and the colour weak the less extreme of the two. It suggests that they think of colour-vision defects as subject to continuous variation : normal, colour weak, anomalous trichromat and colour blind, just as we have arbitrary subdivisions of the continuous grading of intelligence quotients. The term " anomalous trichromat ", will not be used because it is unnecessarily ambiguous. Few truly red-green blind subjects are strictly dichromats, requiring absolutely not more than two primaries to match all spectral colours which they see, both in hue and in saturation. The normal, deviant, colour weak and possibly even the anomalous subjects in my grouping, however, are not trichromats, but require at least four primaries, to the best of our knowledge. If, by " anomalous trichromat " we mean the red and green anomalous, then there is no simple continuity between the red-green weak, the anomalous and the colour blind. The red-green weak are the extremes of variation of the " normal ", while the anomalous and the colour blind are recessives in a sex-linked system of Mendelian characters. The Ishihara Test is cleverly constructed to operate at the juncture of these discontinuous variations with the "normal"; it fails all colour blind and anomalous and includes a proportion of normal and colour weak in its failures if operated on a strict level, though it is inconsistent and unreliable in the way it deals with the colour-weak and normal subjects.

INDIVIDUAL SUBJECTS : GREEN ANOMALOUS

Two green anomalous subjects were found wholly by chance in the sample of 109 men : the frequencies were, 103 normal, 2 green anomalous, 4 red-green blind. This is rather a lower percentage of major red-green defectives than is usually found with the Ishihara Test. The Holmgren Wool test generally gave about 5% of red-green blind, but the Ishihara Test usually gives 7% or more, because it fails anomalous subjects as well as the red-green blind. In this series, in order to be as guarded as possible, two red-green blind men were excluded from the " chance " sample, on the ground that it was known by accident that they were defectives before they were actually called on to do the test. If this knowledge had not been gained beforehand, they would have been in the " chance " sample, and then the proportions of red-green blind and anomalous would have been nearer to what may be regarded as the usual figures.

No red-anomalous subjects were found in this series, even after the most diligent searching for red-green defective friends and relatives of the other subjects.

One green anomalous subject, even after the most careful re-testing and practice at the experiment, had a deviation of $32°$ to the green side in the red-green test, which is 4.85 times the standard deviation (sigma) for the normal group, and yet his range of matches was only slightly greater than the modal range. Neither his range nor his deviation in the yellow-blue test was in the least abnormal. This subject failed outright on the Ishihara Test, and even when he became so expert at it that he knew the correct figures by heart, he was still unable to see them. He was, of course, classed " totally green-blind " by that test. Nevertheless, he had no difficulty with the Holmgren Wool Test: all sixteen of his matches for the green test skein were correct and were made without hesitation, but he chose three slightly blueish pinks out of thirteen matches for the pink skein. In the beads test he had no difficulty whatever, except with the minute and almost colourless pale green beads, which are not generally used in the test at all. He thought they might be " white ". He called the Ilford Spectrum Yellow colour filter " green ", which was found later to be characteristic of the green anomalous, but had no difficulty with colours in daily life except in finding red golf tees in the green grass. On one occasion, in a very quick test, he almost called a green signal light " grey ", and he expressed the view that it " takes a woman to name colours, especially greens ".

The green anomalous are distinguished by extreme deviation in the Rayleigh Equation; and in fact, the Rotating Disks Test, being very polychromatic, does not give them as great a deviation as they have in a test with monochromatic red, green and yellow. They pass Nagel's Card Test easily, though he claimed to be green anomalous himself, and regarded it as especially suitable for detecting them. There is little doubt that the true green anomalous were entirely missed by his test, and that the subjects to whom he applied that term were in fact moderate deuteranopes, as he probably was himself. He claims that the green anomalous are also distinguished by exaggerated simultaneous contrast.

The possibility of enhanced simultaneous contrast in colour-weak, anomalous and colour-blind subjects, will be discussed later. It is probable that the impression that certain red-green defectives have enhanced simultaneous contrast has been due to a failure to understand their use of colour names. The anomalous are almost as particular as the normal in all colour matches. and have few

peculiarities of colour naming, though they often express irritation at the " fancy " names for colours, especially for pastel shades of green and pink.

INDIVIDUAL SUBJECTS : DEUTERANOPES

Two sisters who were deuteranopes must be discussed. The elder was aware that she had a defect, but the younger believed she was normal until tested. The Ishihara test shows her clearly to be a deuteranope, the photerythrous class, because she can read the vermilion figures and not the purple figures on a grey background, which are used to distinguish protanopes and deuteranopes. Those who can read the purple figures but not the vermilion are protanopes. In this test in general she was just able to read the figures intended for normal subjects, but could see those read by the colour blind more easily. Sometimes her reading was a combination of both sets of figures. Her failure on this test was less complete than that of the green anomalous subjects, and in an examination with the Ishihara alone it is not unlikely that she would be classed as " green anomalous " and they as " totally green blind ". This interpretation, which might easily be made by many students of colour vision, would be wholly unjust. Her matching range in the red-green disks test is more than three times as great as that of the anomalous and her mean deviation in this test is about 13 × sigma for the normal. It is true that she rejects the normal mid matching point by a wide margin, which makes her more like the green anomalous than most deuteranopes, but other points have to be taken into account. In the red-green test she saw both disks alike at the fully green end of the scale, but she called them both " red ". It is true that the green anomalous subject will call a certain red-green mixture which looks green to the normal " red " up to the point at which it matches the yellow standard for him, but no green anomalous subject would apply the term red to a saturated green and to the grey standard at the same time. This kind of colour confusion is characteristic of the red-green blind. When the red-green disk became red enough to be distinguished from the standard she began to call the latter " green-brown " and continued to call the red-green disk " red " right up to the fully red end of the scale. This terminology does not imply that she had enhanced simultaneous contrast, as might be thought, but is simply due to her applying the term " green-brown " to the desaturated yellow standard, which she was unable to distinguish from green. Since she rejects the normal mid matching point she might be considered unusually strong in red vision, but this must be taken as

relative to her green vision, which is extremely weak, because she confuses desaturated red and yellow, and even red and grey, and calls both saturated green and grey " red " under certain conditions explained above. Her red vision may be relatively stronger than her green, but her ability to distinguish red and green is exceedingly weak compared with the normal and vastly weaker than that of the green anomalous.

She is normal in the yellow-blue test, but when the yellow-blue disk is on the blue side of the normal matching point she calls it " green ", and the grey standard which matches it in brightness " creamy red ". When the yellow-blue disk is on the yellow side she calls it " red-pink " and the grey standard of equal brightness she now calls " white-pink ". The black surround of the disk she calls " brown ", which is the same essential confusion as her tendency to call both the green and grey " red " : just as grey can be called " red ", so can black be called " brown "; but this must not allow us to suspect her of being a protanope, because her brightness matches for all colours are normal, whereas the protanope invariably makes an exceptionally dark match for red. She is extremely weak in red and green, compared with the normal, though only moderately red-green blind, and her red saturation sensitivity is greatly reduced though the brightness of red is unchanged for her. On the Young-Helmholtz theory such a condition would be inconceivable.

It will be worth discussing the subject's terminology for colours more carefully. Her confusion of terms is partly due to her difficulty in distinguishing desaturated greens from greys, so that in her efforts to use names in the way other people seem to use them, she might apply the term green to a desaturated blue as the colour to which it seems most likely that other people must be applying it. Her confusion is also due to her difficulty in distinguishing between desaturated reds, greens, yellows and greys of equal brightness. Thus when a desaturated blue, which she ventures with some confidence to call " green," is compared with a grey of equal brightness, that grey is called " creamy pink ". The term " pink " she applies to a range of desaturated reds, yellows and greens, and to certain greys, all of which it is difficult for her to distinguish. When the grey is contrasted with desaturated yellow, it is called " white-pink ", but the yellow is called " red-pink ". All desaturated reds and yellows, being alike, may be called " red ", " pink ", " orange ", or " yellow ", according to saturation. " White-pink " therefore means " whiteish-grey " in our terminology; " red-pink " means " yellowish-grey "; and " creamy-pink " means " creamy-grey ",

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because " pink " is her private name for colours often indistinguishable to her, but easily distinguished by her friends, and she has adopted this terminology (ambiguous to us) in order to try to adapt herself to a world of other people who have far too many colour names for her to use for the different colours she sees clearly.

When the colours of the disks are what we should call either very bright or saturated, however, she does not apply the term " pink " to any of them : it is reserved for desaturated or greyish colours. Thus the red-green disk when fully green is very bright, like the bright desaturated yellow with which she matches it for hue, and she applies the more forceful term " red " to both. As the yellow becomes darker and is mixed with black instead of white, it becomes relatively more saturated at the same time, and she calls it " green-brown " in contrast to the increasing redness of the red-green disk. This is not because she has enhanced simultaneous contrast, but because she exploits the term " green-brown " to distinguish a desaturated yellow from a red which she now sees more clearly. This discussion suggests that her private terminology for colours is perfectly rational, and is the result of efforts at adaptation to meet her difficulties over differences almost indistinguishable to her and over the terms other people confidently use for them.

The elder sister was also a deuteranope, but distinctly more colour blind. She was aware that she had a defect, because she had been asked to name the traffic lights in the course of an examination for a motor driving licence in the U.S.A. To the examiner's astonishment she called the green light " grey ", the yellow " orange " and the red " red ", but had no difficulty in distinguishing between them. He was silent for some time from amazement and then decided to pass her. Green is her favourite colour, though it is impossible to believe that for her it can be anything like what normal people call green. On the Ishihara Test she failed completely on every card, and was quite unable to distinguish the figures seen by normal people. Like her sister, she saw the vermilion and not the purple on a grey background, and must be classed as a deuteranope. On this test she is therefore " totally green blind ", and in no way distinguished from the green anomalous subject described above. She took the Ishihara Test home and tested her father, who gave exactly the same result as herself. He firmly insisted, however, that his colour vision was perfectly normal and absolutely refused to come to the laboratory to have a talk about it. She has four paternal uncles, two of whom are said to be colour blind, and two paternal aunts said to be normal. Her mother was believed to be normal and came

to the laboratory to be tested, and her colour vision will be discussed below.

In the rotating disks experiment this colour-blind girl was absolutely normal in blue and yellow, though slightly less sensitive than the very best subjects. In the red-green test her range of matches carried her from the fully green end of the scale very nearly to the red end, with the result that she has a very big range and a moderate green deviation, and easily accepts both the normal mid matching point and that of green anomalous subjects. Both disks looked " grey " to her from the green end until the normal matching point was reached, and then they both began to look " pink ". When they were distinguished in colour the yellow-black-white disk became " orange-pink " and the red-green disk became " purplish-pink ". Finally the " orange-pink " became " orange " and the " purplish-pink " became " red ". Therefore, although the Ishihara Test classified her as " totally green blind ", she has a very large weakness in red as well as in green, and probably has as much as ten times more difficulty in distinguishing between red and yellow than the normal person, as well as confusing red and green. Hence the term " green blind " would be thoroughly misleading in its application to her condition. In a subsequent test which demonstrated her colour vision to a large audience,* this girl misnamed spectrum red as " green ". She is not at all reserved about her colour blindness, but delights in naming colours before her astonished friends, who cannot decide whether she is joking or serious when she calls green articles grey or red ones green. Her mother has to buy her lipstick, and this shows that difficulties in daily life are not with greens alone.

The mother of the two colour-blind women just described, was believed to be normal in colour vision, but on being tested with the rotating disks she proved to have a small blue weakness and more than twice the modal range in red and green, but she had no deviation in the red-green test. She passed the Ishihara Test easily, though she was able to read the figures supposed to be visible only to the colour blind. She believes she has no colour-blind relatives, and, as her father was a draper, she thinks that he could not have been a red-green defective, but, as will be seen later, this is not adequate evidence, because many colour-blind people are extremely clever at distinguishing colours under conditions of lighting which they select themselves, and when working with materials and articles of which they often already know the colour names.

* British Psych. Soc., Glasgow Meeting, 1944, at Jordanhill T.C.

In this family, from what we know of sex-linked inheritance, the most probable state of affairs is that the father is a "deviant" deuteranope, like his daughters, and that the mother is heterozygous for the same red-green defect. The maternal grandfather may have been a "deviant" deuteranope, but, on the other hand, the mother may have inherited her heterozygous condition from her own mother, who could have gained it either from the male or female side of her family. Daughters of matings between a heterozygous woman and a colour-blind man (presumably of the same type of defect) have an equal chance of being colour blind or heterozygous, and in this case both were colour blind.

Another subject was rejected in a colour-vision test for the railway services. He has never believed that he was colour blind, and remains a little resentful at being rejected, after more than 30 years. His yellow-blue vision is excellent, but when he sees the yellow disk as different from the standard grey he calls it " reddish " or "pinkish", reserving the term " yellow " for more brilliant and saturated shades of what is to him essentially the same colour as red or green. In the Ishihara Test he failed completely, and he is a clear deuteranope. In the red-green disks test he has a very wide range, but distinguishes the most saturated green from the standard, calling it " buff " and the standard " yellow ". At the red end he is again able to distinguish the two disks, now calling the red one "pink" and the yellow one " yellow ". This subject is specially interesting because he has the central scotoma for red-green vision which is met with occasionally. His fixation of the disks often allows part of the margin of a disk to fall outside the central scotoma, and then he notices more colour difference at the edge than at the central parts of the disks. In consequence he often suspected that he had missed a real colour difference, and complained that the disks seemed more deeply coloured at their margins than in the centres. This difficulty occurred only as we approached the red end of the scale, and all colour matches which were doubtful on this account were excluded. If they were included his range would be increased by at least half in the red direction.

It is well known that the possiblity of meeting with such subjects makes it essential that all tests of colour vision should be done with test objects small enough to be confined to foveal vision when fixated directly. For instance, subjects of this type might be able to pass the Ishihara Test if they were allowed to bring it close to the eyes. Hence, if any subject asks to be allowed to come nearer to the test objects than the standard distance, special caution must be taken

in examining him. The excuse that he is short-sighted is not accept-able : I have tested many short-sighted subjects with and without their spectacles and found no difference in colour vision with the usual tests.

Professor W. J. B. Riddell has told me that he believes that foveal colour blindness is due to heavy smoking of tobacco, and certainly this subject was a heavy smoker. It was not possible to persuade him to give up smoking for a month and then re-test him, because he did not agree that he had any defect. However, his red-green matching range was ten times the modal range and he had a deviation in the green direction amounting to $8.5 \times$ sigma for normal subjects. Many men are heavy smokers, however, without being colour blind, and some colour weakness may be necessary for smoking to have this effect.

INDIVIDUAL SUBJECTS : A PROTANOPE

In order to illustrate the characteristic reactions of protanopes in the experiments here reported, and in daily life, it will be convenient to take two colour-blind women again. Like the deuteranopes just discussed they are sisters, and this time it will also be possible to discuss the colour vision of their father. The elder sister has great difficulty in seeing red berries on a tree, and knows that she confuses greens with browns. She never makes a mistake with yellow, however, unless it is greenish, but confuses blue, heliotrope and pink. She failed wholly on the Ishihara Test, falling decidedly into the so-called " totally red-blind " class. She is scoterythrous, a protanope, and she thinks the black sector of the standard disk might be red.

" ENHANCED " SIMULTANEOUS CONTRAST[14]

In the yellow-blue disks test she has a decided weakness in blue, and calls the blue sector of the disk " pink " (a most characteristic error of the protanope), while the standard grey she calls " green ". When the yellow-blue disk is yellower than the standard she calls it " beige " and the grey one " pink ". This terminology suggests that she has exaggerated simultaneous contrast. The colour blind are striving to apply the terms we use, though they see far smaller differences of hue and saturation than we see. If their own simul-taneous contrast effects are no greater than ours, it would be true that they try to apply colour names to these small differences just as they also strive to use them of real colour differences, for them

equally small, which are what they see when we see differences that are very marked. Since simultaneous contrast produces only relatively small differences for us, compared with the marked differences of hue and saturation with which we are familiar, we do not tend to apply emphatic colour names to them so freely as the colour blind do. Even if their simultaneous contrast effects were smaller than ours, it would still be easy to understand the peculiarities of terminology which make us think they are greater. In their efforts to convince themselves and us that they can see colours as easily as we do, they tend to apply emphatic terms to minute differences. A hue faintly bluer than mid-grey is as different from it as red is from green for them, although the red-green difference is vastly greater for us. Hence it is as rational from their point of view to call the blue " pink " and the grey " green ", thus suggesting exaggerated simultaneous contrast, as it is to call the red " orange " and the green " yellow ", thus revealing their colour blindness. If the colour blind do succeed in applying our terms correctly to the small differences of hue and saturation which they see, then we may imagine unsuspectingly that they can see the colours as vividly as we do. This is a mistake. Similarly, when they apply the terms, still correctly but in exaggerated ways, to the very small differences produced by simultaneous contrast and often existing apart from it in colours which they can see, we readily suppose that their colour differences are again as great as their terms suggest. So we assume that they must see great differences where we see small, because they still apply their technique of using emphatic terms for small differences, and we infer enhanced simultaneous contrast.

Suppose that this subject sees a pale blue, which she calls " pink " because it is a colour she would confuse with pink. As a result of her habitual striving to name colour differences in our way, she calls the contrasting grey " green "; then it is easy for us to suppose that she can see green by simultaneous contrast better than she can directly. Similarly, when the yellow-blue disk is yellower than the standard, she calls it " beige ", which is the same as green to her, and then she calls the grey standard " pink " in order to emphasise the scarcely visible difference. We, however, might fall into the error of thinking that she sees pink better by simultaneous contrast than normally. No doubt there is some simultaneous contrast, but there is no adequate evidence that it is greater in the colour blind than it would be for us. Indeed, on any theory of colour vision it would be difficult to suppose that it was greater in the colour blind, because colour blindness is a reduction defect, and what is lost in direct

experience cannot easily be over-compensated by contrast, except in the secondary way described. What the colour-blind person does is to confuse small effects of contrast with the equally small true colour differences which he sees, because both are as faint to him. In a class of fifty students it is usual to have to train a certain number to see simultaneous contrast effects, but never necessary to train a colour-blind person, because he has been practised in observing minute colour differences diligently but without intention since he was an infant. The reason why Nagel has used the presence of what he believed to be enhanced simultaneous contrast to distinguish what he called the anomalous, is found in his application of the term anomalous to those who are moderately colour blind rather than to the truly anomalous, which is a very common way of using the term. These moderately red-green blind, though not the truly anomalous, are the very subjects who constantly see minute differences of hue and saturation where we see great differences, and they are the ones who make the kind of over-compensation explained above. Nagel found correctly that this sort of colour naming error was characteristic of those whom he called the " anomalous ", but they were not anomalous and the error was not due to enhanced simultaneous contrast. The extremely red-green blind do not see these small and often nameless differences at all, and they escape the sort of error of naming which suggests exaggerated simultaneous contrast.

In the red-green disks test this subject has a large range of matches and a marked deviation to the green side, although she is a protanope. In other words, although she has the characteristic darkened red vision of the protanope, she is still better able to distinguish red than green from yellow of equal brightness. This would be incomprehensible on the Young-Helmholtz theory. At the green end she calls the green disk " beige " and the standard " white "; in the middle of the range she calls both " yellow "; at the red end of the scale she calls the red disk " pink " and the standard " orange ".

OTHER PROTANOPES

Her sister also knew she was colour blind most of her life, and she, too, confuses pink and pale blue, while her most distressing mistake is to take red for black, or the reverse, and the black sector of the standard disk she called " red ". She failed completely on the Ishihara Test and was classed by it as a protanope. In the yellow-blue disks test she is weak in blue, but her contrasts in this test are between " blue or pink " when the yellow-blue disk is bluer than

the standard, and "pink or blue" when it is yellower. This terminology is easily understandable. She confuses desaturated reds and yellows because of her red-green blindness, and she confuses blue and pink because she is a protanope and the red in pink is subtracted for her, leaving only pale blue. Hence in doubtful circumstances she can use the term " pink " for either yellow or blue in contrast with a grey of equal brightness. Her alternative terms showed that it seemed more likely to be blue when it was bluer and more likely to be pink when it was yellower, which is quite correct according to her form of colour vision. In the red-green disks test she has a little more than half the matching range of her sister, and is decidedly less colour blind, though she has equally darkened red. At the green end of the scale she calls the green disk " pink " and the standard " orange "; at the red end she calls it " yellow " and the standard " pink ".

The father of the last two subjects was not only red-green blind, but had lost the use of his right eye as a result of an accident sixty-nine years before the present tests were done. He died recently at the age of 81. He believed that he had better colour vision than his daughters, but, according to the test he was decidedly worse. His business was with gems, on which he was a well known expert, and he explained in detail that he never had any difficulty in distinguishing gems by their colour and was always correct. Like his daughters, he was of the darkened red type, a protanope, and failed completely on the Ishihara Test. He had a weakness in blue exactly similar to that of his daughters, and since these three were the first protanopes tested in detail here, it seemed possible that the weakness in blue might be characteristic of them, and might account at least in part for their marked tendency to confuse pink and pale blue. However, these two hypotheses were not borne out by later studies of protanopes. It is not a characteristic of protanopes to have a weakness in blue, and although it is usual for them to confuse blueish pinks and magentas with pale blue, this is due to their greatly darkened red, which cuts out most of the red and leaves mainly blue in blueish pinks. For example, to a protanope rose pink may be exactly the same as sky blue; but to a deuteranope it will more often be almost colourless; because both see the red in it as a yellow which is complementary to the blue, but for the protanope that yellow is almost too dim to have any effect and it leaves the blue outstanding.

In the yellow-blue disks test this subject called the standard grey and the variable " yellow " when most people see it as bluer, but he

called the standard "blue" and the variable "grey" when most people see it as yellower. This peculiar terminology was due to the same efforts to adapt himself to our colour names as in his daughter, who used the term "pink" in the yellow-blue test where he used "yellow". For certain very desaturated shades, the terms "pink", "blue", and "yellow" might be synonymous, and it is a matter of chance which the subject happens to use unless he is corrected. Having called the variable "yellow" (="pink") when it was bluer, because blue and pink are indistinguishable, he called the standard "grey" correctly in contrast. At the other side of his matching range, when the variable seems yellower to most people, he applied the term "grey" to both standard and variable. The double complication is caused by the two facts, first that desaturated blues and pinks were identical to him within certain limits, and second that desaturated blues and greys could also be identical. Then his terminology depended on what he happened to start with, and in this test the errors continued almost consistently.

In the red-green disks test he called the green disk "yellow" at the greenest end, and the corresponding standard "grey", and at the extreme red end he used exactly the same terms. Red was greatly darkened for him, since he required 90° more black than deuteranopes, although it was subsequently found that the disks test, owing to the polychromatic nature of its red, does not reveal the darkening of red at anything like its full value for protanopes. It is likely that this darkening contributed to his ability to judge the colours of gems. He admitted in conversation that a dark coloured gem must be either blue or red, and for the most part saturated blues were well perceived by him, and he knew that a dark coloured gem which is not blue must be red. He did not need to think this out: it was perfectly automatic. Light coloured gems will be either yellow or green, and the difference between these colours for him was determined by the less saturated character of green. Pale blues were perceived as blue or grey, and pink was an alternative to blue under some circumstances, but, generally speaking, it was found that rose was called "blue" rather than blue "rose". It is very difficult to believe that a man with such an extreme colour-vision defect was as competent as he claimed to be in dealing with the colours of gems. One would like to make certain carefully planned tests. It is unusual for precious stones to be wholly unnamed by any of the parties to a transaction, and the colour blind man may rely unconsciously on naming more than he thinks. Precious stones also have their characteristic crystalline structure, "water" and refractory properties, and are also cut differently,

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according to their kind. Nobody who had spent his life working with them, not even a protanope, would confuse a sapphire and a ruby, or a diamond and an emerald. This subject was certainly most clever at making the utmost use of what colour sensitivity he had, and exploiting characteristic brightness differences and the shapes and sizes of familiar objects to help him out. This exploitation of secondary aids is wholly unconscious. It is hardly surprising that he left the laboratory completely unconvinced of his colour blindness, but fully realising his daughters' defects.

The third sister, who was believed to be normal in the family, also came to the laboratory to be tested, and proved to be decidedly red-green weak without any darkening of the red, and to have the characteristic blue weakness of the other members of the family. She made eight mistakes in the Ishihara Test, and it is doubtful if she would have been passed on a strict examination. She had the peculiarity of requiring the yellow sector of the standard disk in the red-green test to be reduced to 45° and then to 20° before the matching at the green end of the scale could be carried out. She had a range of about twice the mode, whereas her father's range was at least ten times as great as hers. She had a considerable margin of uncertainty on the green side and this is the smallest possible estimate of her range.

It is believed that the mother was normal in colour vision, but she was dead, and it is difficult to draw confident inferences from hearsay evidence, especially as one sister had been considered perfectly normal until systematically tested. We have now before us records of two families in each of which there were two colour-blind sisters ; a colour-blind father, and a mother believed to be normal in one family, and known to be slightly red-green weak in the other. In the family in which the mother was not tested there was a sister who was slightly red-green weak. All the colour-blind members were of the same type in each of these families—deuteranopes in one and protanopes in the other, and, as far as could be ascertained, they had a similar degree of defect. This is good evidence that the type and degree of defect are inherited : when the father was a protanope the daughters were protanopes, not deuteranopes, and vice versa.

The last protanope to be dealt with here was doubtful that he was more than slightly defective, but thought he confused red and yellow sometimes, though he was able to name green correctly and did not confuse red and green. He was very willing to be tested, almost enthusiastic, and was also a little over-confident about his

judgments of colours. He failed wholly on the Ishihara Test, and was able to see one vermilion figure on a grey background but none of the purple ones, so this test would probably have classed him as a doubtful deuteranope. He reported that his maternal uncle was considered colour blind, but a test for him could not be arranged. The first time the present subject came to the laboratory he was very good in the yellow-blue test, but called the yellow-blue disk " pale blue " when bluer than the standard and " reddish " when yellower. The corresponding standard he called " red-brown " in contrast to the pale blue, and " not white, might be anything " when the variable was " reddish ". In the red-green test he called the red-green disk " green " and the standard " yellow " at the green end of the scale, but at the red end he called the red-green disk " pink " and the corresponding standard " green ", " brownish yellow " or " red " at different times, as if experimenting with different colour names to see which I would encourage by a smile or gesture, and which would excite disapproval. He was willing to admit that the disks were alike only at the normal matching point when he called them both " green ". He was known to have had disputes with his sister about the colours of flowers. In addition, his colour naming was so suggestive of red-green blindness, that the result of the rotating disks test was considered unsatisfactory, and he agreed to come back for a re-test. It was particularly important to do this, in order to find out with what degree of certainty colour-blind subjects could be detected by the rotating disks test, and to see what types of subjects tended to escape detection, if any, and under what conditions they might be missed.

In the re-test an experienced assistant was present to watch the proceedings and make notes. This time he was given Holmgren's Wool Test, Edridge-Green's Bead Test and Nagel's Card Test in addition to repeating the rotating disks test. In the wools test he was extremely slow and particular, and tried out numerous brownish skeins when matching the green standard skein. This almost endless consideration of fawns as possible matches for green, with a frequent quick glance at the tester to see what his expression reveals, is very characteristic of the red-green blind, whether darkened red or not. When matching the pink standard skein he picked up in succession : 1, prussian blue; 2, pale blue; 3, peacock; 4, pale blue again; and 5, mauve. Then he asked if there were really any skeins the same colour as the pink. He was told that it was his business to find them if there were any. Then he picked out the one skein which is an exact match, saying that it was " quite good " with a doubtful

air, as though he would be ready to reject it if the tester frowned. Finally he examined the pale blue and discarded it doubtfully for the third time. When matching the saturated red test skein he examined and discarded dark brown and reddish brown in succession. Then he chose some reddish and brownish skeins as " nearly matching " it. A performance of this kind could leave no doubt that we were dealing with a red-green blind man, and gave a strong presumption that he was a protanope.

In the Edridge-Green Beads Test he chose red beads straightaway and put them in the red hole; then he considered several dark browns and finally added one brown bead to the reds. In the green hole he put yellow, fawns and greens; in the yellow hole nothing but yellows, but at this stage he found an additional green bead and put it in the green hole. In the blue hole he put blue and violet; he considered and discarded magenta and dark greenish blue, but added a black bead to the blues.

On Nagel's Card Test he made a doubtful pass, and showed evidence of what Nagel calls the heightened simultaneous contrast of the anomalous subjects. For reasons given above it is far from clear that the anomalous do have heightened contrast effects, and this subject proved to be a moderate protanope and not anomalous. Subjects like him tend to see a number of shades and hues of quality uncertain to them, and they tend to exaggerate any colour differences which they can see in attempts to convince themselves and the normal that they see colours efficiently.

After these tests the red-green disks test was repeated with a more matter-of-fact, straightforward and less persuasive technique, and the subject made a number of doubtful matches which gave him a wide range in red and green with a deviation to the red side. Throughout all these tests it was clear that this subject was highly contra-suggestible about colour matches. It was as though he felt that there was always danger that if he agreed two colours were alike he would be laughed at for making a mistake. This was coupled with an exaggerated confidence. If asked in the ordinary way, " Are the two disks the same ? " he would invariably answer, " Oh! No! Absolutely different ", or " Not the slightest resemblance!" Consequently it was necessary to avoid any direct questions which might provoke resistance, but instead to ask him to describe the two disks, without mentioning to him any words such as " alike " or " different ". He then explained at certain points that they were indistinguishable to him. Even under these conditions he was unwilling to commit himself to a colour match, and usually added a

qualification, such as " Nearly!" as an afterthought, for fear that he might have been wrong. By his habitual technique of refusing ever to make an exact match, he succeeded in giving the impression that he was very sensitive to colour differences, but since he regarded the pink skein in the Holmgren Wools which is exactly the same as the pink standard skein as " quite good " with an air of doubt, it is clear that he was often pretending to see colour differences which do not exist for him (or for anybody else, in this example). In the disks test there was no doubt of his having the darkened red of the protanope, and, indeed, all the tests confirmed the same interpretation. Thus he selected dark brown as a possible match for red in the wools and beads tests, and he also considered peacock, pale blue and mauve as possible matches for pink in the wools, and magenta as a possible match for pink in the beads. His range of four times the modal range in the red-green disks test showed beyond doubt that he was red-green blind and not anomalous, and this range easily included the normal mid matching point.

A subject like this taxes the tester's ability to the greatest possible degree, and he has to be almost more of a clinician than a tester to penetrate the numerous defence mechanisms utilised by the subject to protect himself against the suspicion that he is not perfectly normal. Not the least of these defence mechanisms was an engaging readiness to submit to any tests that could be devised. Nevertheless, the persistent over-confidence, coupled with endless hesitation over colour matches which a normal person would not think twice about, on the pretext that he is exceptionally particular, and his unwillingness to accept any match, even that normally accepted without hesitation, laid him open to suspicion. If uncertainty persists in such a case after repeated tests, it is better to class the subject as colour blind than to give him the benefit of the doubt. An almost equally difficult subject who was a moderate deuteranope was found later.

INDIVIDUAL SUBJECTS : A YELLOW-BLUE DEFECTIVE

The last colour-blind subject to be considered here falls into the class of yellow-blue defectives. He was discovered in an interesting way. Another man who was tested had a small red-green weakness and a small weakness in blue as well. He had some difficulty with the Ishihara Test and could hardly pass it, and, when asked if he had any colour-blind relatives, he said one of his two sons must be colour blind because of his great difficulty with painting at school. This son was tested later. He was an extreme deuteranope. Since

red-green blindness is not known to be passed from father to son, it did not seem likely that the father's small weakness was inherited by his son as colour blindness, and efforts were made to test the mother, but she lived some distance away and has not succeeded in arranging a visit to the laboratory. We, however, had no difficulty in persuading her father to come for a test, and, since any man whose daughter's son is red-green blind may be red-green blind himself, this seemed important. When he came, however, the grandfather of the colour-blind boy explained that he had always had some difficulty with blues and greens, but did not think he was colour blind. He found the Ishihara Test rather difficult, taking a long time and complaining that he should have brought his reading glasses. The yellow-blue figures in Stilling's Tables he was almost unable to read, and he was wholly unable to read the green-blue plates. In the beads test he put red and pink beads in the red hole; blue, peacock and greenish blue in the green hole; orange only in the yellow hole; and green and greenish blue in the blue hole. When asked at the end of the test why he had left out a certain group of beads, he said they were " white "—these were the yellow beads.

In Holmgren's Wool Test he matched the green, pink and red skeins correctly, but, owing to his peculiar response in the beads test, certain additional colour matches were asked in the wools test. He had great difficulty in distinguishing desaturated blue and yellow skeins from fawns of equal brightness, and in distinguishing green from greenish blue.

In the red-green disks test he called the yellow sector " white " when it was at rest, and did not know whether the green sector should be called " blue " or " green ". He proved to have a moderate range in red and green with a slight deviation to the red side. He was just too sensitive to be classed as colour weak in this test. In the yellow-blue disks test he had a range as large as that of moderately red-green blind subjects in the red-green test, and again called the yellow sector " white ". His yellow-blue range was five times the modal range, with a marked deviation to the blue side.

From all these tests it was clear that he was slightly weak in red and green, but exceptionally weak in yellow and blue, more in blue than yellow. If the red-green and yellow-blue results had been reversed, a slight weakness in yellow and blue and a weakness as great as his in red and green, he would have been classed without hesitation as a red-green blind subject. Hence it would be reasonable to consider him yellow-blue blind. There is, however, an important difference. It will be seen that all forms of red-green blindness are

products of discontinuous variation and are subject to sex-linked inheritance. Yellow-blue defects, however, are subject to continuous variation and are not sex-linked. This subject was an extreme of a series of yellow-blue defectives, who could be arranged to fill in a normal curve which would include him and all the yellow-blue weak subjects as well as the normal. Such a series of subjects would be the same for men as for women and could include both sexes indifferently. Three facts give strong suggestion of the truth of this hypothesis : first, the great rareness of extreme yellow-blue weak subjects; second, the relative frequency of intermediates; and third, the frequency of moderate yellow-blue weaknesses in women, which is equal to that among men. In red-green vision the state of affairs is quite different : women are more often colour weak than men, but men are much more often colour blind; and the extremes are more common than the intermediates.

It would be very difficult to fit this subject into either the Young-Helmholtz or the Ladd-Franklin colour-vision theory. On the Young-Helmholtz theory he could not be classed as " red-blind " or as " green-blind ", because his colour vision for these colours is almost normal; and he could not be classed as " blue-blind " because his weakness in yellow is nearly as great as that in blue; but yellow-blue blindness is theoretically non-existent on the Young-Helmholtz theory. On Ladd-Franklin's theory a person cannot be extremely weak in yellow and blue without being at least equally weak in red and green. He would be equally difficult to fit into any of Edridge-Green's seven classes of defectives, for he combines the good red-green vision found in hexa- and heptachromics with weaker yellow-blue vision than usually found in dichromics. Such a case cannot be accounted for in terms of pigmentation of the retina or other transparent parts of the optical system, because as much blue as yellow pigment would be needed, and, unless such pigments were almost monochromatic they would affect the whole spectrum and reduce red and green to a much greater extent than in this subject.

It is specially interesting that this subject's grandson should be red-green blind, and has no noticeable weakness in yellow and blue, but it is most unfortunate that the mother has not been able to come for a test. We may make a hypothesis that the yellow-blue blindness, when transmitted, at least in this case, became red-green blindness in the daughter's son. This would fail to accord with the discovery that types of red-green blindness are inherited strictly in their own form. The other hypothesis, that the mother was heterozygous for red-green blindness and gained it from her mother and not from her

father, is more probable. In this case the son's red-green blindness will have had no connection, either with his father's weakness in red and green or with his maternal grandfather's yellow-blue defect, but will have come from his maternal grandmother's mother or father.

Many people doubt that yellow-blue blindness exists, but this case seems to put the matter beyond doubt, and also reveals a number of interesting points about its relation to red-green defects. If it is true, however, that yellow-blue blindness is simply the extreme of a continuous variation, then we shall have more difficulty in defining its limits than we have with red-green blindness, and the question whether the term " yellow-blue blindness " ought to be used at all may be raised.

Chapter 4

THE "PAIRED COLOUR-FILTER TEST"

THERE are many objections to the use of rotating disks as described in the last two chapters. The rotators are heavy and must be screwed down on a solidly constructed table to withstand vibration. A motor and shafting are needed, and a special lamp situated in an exactly standardised position. An easily movable test for colour vision could not be constructed in this way, and all subjects to be tested would have to visit the laboratory. In addition, the changing of the coloured disks causes delay and must be done very carefully if errors in adjustment are to be avoided. There is a risk that the papers used may become soiled or oily unless kept and handled with great care, and they are easily torn. It is difficult to replace stocks of coloured papers with identical samples. The hues and fractional reflectivities of the papers are not scientifically standardised, surface textures may vary slightly according to colour, and there is no hope of getting coloured papers which are even approximately monochromatic. The noise and vibration caused by the motor was a great nuisance. A number of the subjects were under the impression that the experiment with rotating disks was really about the effects of noise on sensitivity to colours.

THE ANOMALOSCOPE OR COLORIMETER

In order to overcome these difficulties, it was suggested by Mr. V. R. Paling that gelatine colour filters could be used. At first an apparatus for this purpose was made, in which filtered lights of the required colours from different sources were combined by means of mirrors, and viewed by the subject of the experiment as seen on a ground glass plate. This proved very heavy and required powerful lamps which made over-heating a serious problem, and, owing to these and other objections, it was soon abandoned in favour of an apparatus in which light was combined by means of lenses.

The lens apparatus was essentially a colorimeter, made along the lines of Houstoun's instrument,[1] but with certain alterations making it suitable for the tests for which it was needed. It was designed to

fulfil the functions of the rotating disks of the previous experiments. It is illustrated in Diagram VII, and consisted of a wooden box divided into three compartments. The first compartment contained
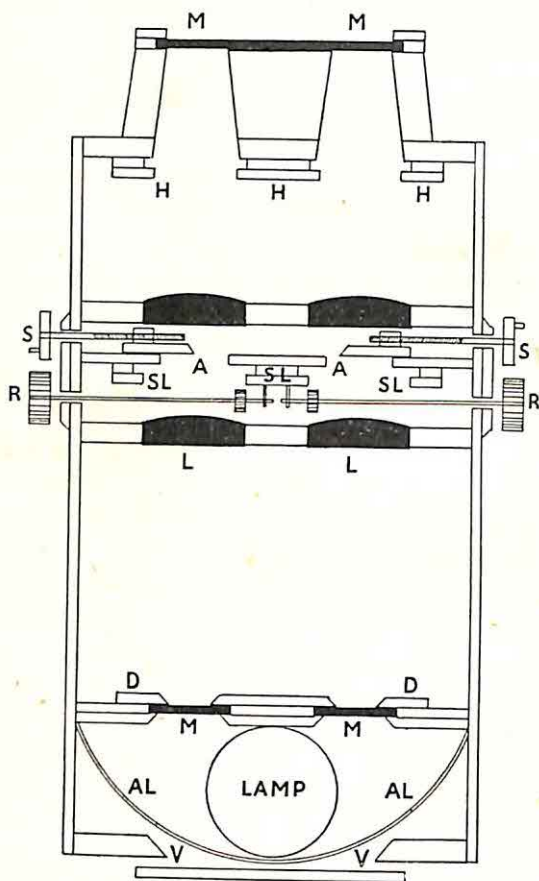
Diagram VII.   Plan of the Colorimeter or Anomaloscope

M = Milk Glass Plates
H = Holder for Daylight Filters
S = Shutter Control Screws
R = Knob and Ratchet Slide Controls
SL = Slide Holders
A = Apertures of Lenses
L = Lenses
D = Disk with Apertures for Light Spots
AL = Aluminium Reflector
V = Ventilator

a 100-watt daylight-blue lamp, and later replaced by an ordinary pearl lamp and half-watt-to-daylight filters. Two openings each half-an-inch square were cut in the partition and covered with milk glass. The light from the lamp was concentrated on the slits by an

aluminium reflector. The openings were three inches apart. In the second compartment there were two achromatic lenses of 55 mm. diameter and 15 cms. focal length. Each was placed directly in front of one of the openings and focussed upon it, so that light is dispersed evenly from the milk glass plate over the opening and radiates towards the lens. When transmitted by the lens it is formed into a parallel beam. These are the colimator lenses. In the third compartment there were two more lenses exactly like the first pair, each of which was placed precisely to catch and transmit one parallel beam and to bring it to focus upon a milk glass screen. This screen was placed in the front end of the box and caught two images, which are the same size as the openings. In many of the experiments a black paper guard was placed behind this screen, in which there were two round holes exactly in the right places to admit the two images, and a trifle smaller so that they cut off the edges of the images sharply all round.

The parallel rays between the pairs of lenses were passed through the partition between the second and third compartments by means of two apertures 35 mm. square. Each of these apertures was fitted with a horizontally sliding rectangular shutter controlled by a milli-metre screw and carrying a pointer which travelled along a milli-metre scale. The partition also carried slots and controlling pinions by means of which slides fitted with ratchets were moved up or down, one in front of each aperture. The two slides in turn each carried slots in which square colour filters could be placed, two in each slide, one above the other. Each slide carried a scale which could be read against a pointer fixed to the partition beside it. When one of the slides was in its highest position, the lower colour filter was opposite the aperture, and the image formed on that side of the milk glass screen in front of the box would be in the colour of that filter. The corresponding scale then read zero. When the slide was in its lowest position the upper filter was opposite the aperture and the image was in the colour of that filter. The scale then read 35 mm. In any other position of the slide the aperture was covered by parts of both filters, and, since every portion of the lens in front of the aperture taken separately forms a complete image and not part of an image of the slit, there will be an image on the front screen in the combined colours of the two filters always in the proportions in which they divide the aperture between them. In other words, as the slide is moved from zero to 35 mm. of scale reading, so the image changes colour from that of the lower to that of the higher filter, and the intermediate positions give mixtures uniform in colour over the

whole image and intermediate between the two filters. The right slide was fitted with an additional slot in which a second filter would be placed in front of the upper filter. The purpose of this will be explained later. On principles similar to those given above, the horizontal shutters controlled the brightnesses of the corresponding images, the aperture being closed when the shutter reading was zero and open when it was 35 mm. Since the colour filters divide the aperture horizontally and the shutter divides it vertically, the colour proportions in the image are not altered by the brightness control of the shutter. Thus any colour mixture can be dimmed to any extent without changing its hue, and its hue can be changed without changing its brightness (except in so far as the two colour filters are of different brightnesses). In addition, just behind the milk glass screen, covering the position of each image, there is a fixed colour filter holder, so that the beam of light forming the image may be filtered again if necessary, as, for instance, with a daylight-blue filter.

At a later stage the original openings cut in the partition between the first and second compartments were replaced by a circular aluminium disk about six inches in diameter. Pairs of holes were drilled in this disk in such positions that any pair would form two apertures of the same size, with their centres three inches apart, one corresponding to each of the original openings. The disk could be turned by pressure of the thumb, and any pair of holes could be moved into position as required. In this way the images could be any of the following sizes: $\frac{3}{4}$, $\frac{1}{2}$, $\frac{3}{8}$, $\frac{1}{4}$, or $\frac{1}{8}$ inches in diameter, as these were the sizes of the pairs of holes in the aluminium disk. Another disk could be made easily with holes any size required, within the limits of the optical system.

The subject in the experiments with this colorimeter or anomaloscope sat at a distance of $1\frac{1}{2}$ metres from the milk glass screen, and the apparatus was placed high enough to bring the images to the level of his eyes. The experimenter is able to stand at the right-hand side and control the shutters and slides in the dark while he watches the spots of light and can see what the subject is viewing. The room was darkened, and excessive streaks of light from the box were controlled with a black cloth. The spots of light are well within the limits of foveal vision, and the subject must look from one to the other in order to compare them. He cannot fixate a point between them and view them together, because they are too far apart for that to be satisfactory to him, and, since they are not adjoining, he cannot fixate the dividing line between them while looking at

them, and this avoids the difficulty that fatigue of a given area of the retina for a given colour might tend to decrease the sharpness of contrast between the spots. The experimenter may use an electric torch when he wishes to read the scales ; but there is sufficient light for the scales of the slides to be read while the experiment is in progress, and the turns of the screw for the shutters can be counted and are one millimetre each. The images are clear and have sharp edges. They are seen against a uniform dark background, and, since they are not adjoining, simultaneous contrast effects are reduced to a reasonable extent. The colours change uniformly over all parts of the images, and are accurately controlled in hue by the movement of the slides, and in brightness by the shutters. Either image can be used as standard and the other as variable, according to the requirements of the experiment. Many interesting experiments can be carried out with an apparatus of this type. For example, one of the spots can be cut out altogether and the other used for measurements of dark adaptation. Some of the colour experiments which can be done with it will be described in the following chapters. It is portable, and can be set up in any dark room. It utilises colour filters which are accurately made and standardised, easily cleaned because they are set in glass, and which can be changed in the slides readily and without delay. The absence of noise and vibration from the quarter horse powe motor of the rotating disks experiment was a great advantage.

LUMINOSITY OF THE TEST SPOTS

It was important to know the luminosity of the images at the surface of the milk-glass diffusing screen viewed by the subject.

TABLE 22

OBSERVED DATA FROM WHICH THE LUMINOSITY OF THE COLORIMETER LIGHT SPOT WAS CALCULATED, ALL COLOUR FILTERS OMITTED

	Light Spots				Photometer Cell
Diam. in inches	1/4	3/8	1/2	3/4	$2^{23}/_{64}$
Diam. in Mms.	6·35	9·53	12·70	19·05	60·0
Area in Sq. Mms.	31·67	71·25	126·67	285·02	2820·6
Ratio	1·0	2·25	4·00	9·00	89·1
F-Candles (measured)	0·06	0·15	0·27	0 ·62	(calculated) 6·14
Ratio	1·00	2·50	4·50	10·33	102·3

A Holophane-Edgcumbe Auto-Photometer, kindly lent by Professor Bernard Hague, was used. This instrument has a light-sensitive cell six centimetres in diameter, but the diameter of the test spot was $\frac{3}{4}$ inch at its largest. Hence the measurements shown in Table 22 were made with the sensitive cell of the photometer against the surface of the milk-glass screen and the light spot in the centre of the cell. This table shows that the brightness of the light spot as measured on the photometer is closely proportional to the area of the sensitive cell used, and the spots would measure about 6.14 foot-candles (omitting all colour filters from the apparatus) if it were the full size of the photometer cell.

THE " PAIRED COLOUR-FILTER TEST "

Along the lines of Houstoun's colorimeter experiment,[1] a set of paired colour filters was made up, with gelatine filters set between photographic glass plates. Each of the filters was $3 \times 1\frac{1}{2}$ inches in size, and consisted of two $1\frac{1}{2}$ inch squares of coloured gelatine set closely together without any gap, and held between glass plates with bound edges. Two filters of this type were made in each of the following pairs of colours : red and green, orange and blue-green, yellow and blue, yellow-green and violet, and green and magenta. All pairs except the red and green were complementary. The technique for their use will be described shortly.

These filters are not monochromatic, and Table 23 shows the colours transmitted by the four which were used most in the experiment: red, green, yellow and blue. They are much the same as the colours reflected by the coloured papers used in the rotating disks experiment. The yellow and blue are complementary, but the red and green form a desaturated yellow when mixed. All these colours are very bright, and, indeed, this experiment can be done in daylight.

TABLE 23

APPROXIMATE TRANSMISSION BANDS OF THE RED, YELLOW, GREEN AND BLUE POLYCHROMATIC FILTERS

Red	Yellow	Green	Blue
Red; Orange; some Yellow.	Red; Orange; Yellow; Yellow-Green.	Some Yellow; Yellow-Green; Blue-Green; some Blue; a little Red.	Green; Blue-Green; Blue; some Violet.

The " paired colour-filter test " was devised in the hope of forming a rapid and efficient test of colour vision, which would be of practical use. Its limitations and the results obtained with it will be described. The technique was to place the two red-green filters in the colorimeter slides and to turn the pinions until one image was slightly green to the experimenter and the other slightly red. Each filter was marked so that it was always used in the same slide, the same way up and facing the same direction. When the filters were set as described above, the subject was asked to name the colours seen. In doing the experiment the sides showing the two colours were varied at random from one subject to another, so that a departing testee could not warn the next comer what to expect. Provided the red and green shown are only slightly saturated, the first step in this test should differentiate the normal, colour blind and anomalous, because the normal named the difference correctly, the red-green blind will report no difference between the two spots, and the anomalous will name them incorrectly. In actual practice it was found that the colour blind sometimes name the spots incorrectly and the anomalous sometimes say they are alike. In addition, many colour-blind subjects are able to identify the more saturated hue correctly as red and guess that the other is green, and this was especially true of protanopes, who could pick out red by its darkness.

After the first step, the subject was told that the colours would be brought nearer and nearer in hue (if he saw a difference), and that he was to find the position at which they were exactly alike in hue and at the same time neither reddish nor greenish. The slides were then moved little by little until the subject agreed to likeness of hue, and then moved up and down together until the position which was neither reddish nor greenish was found. The two slides would then have the same scale reading, and the two images would be identical and yellowish in appearance to the experimenter, who had good colour vision, unless the subject was anomalous, colour weak, deviant or colour blind. If he was anomalous the two images would look to the experimenter very green or red accordingly, but still alike. If he was colour weak there might be a slight difference between their colours to the experimenter's eye. If he was a deviant they would be alike but slightly reddish or greenish. If he was colour blind there might be an extreme difference in their hues and scale readings. For the normal and anomalous the remainder of the test was then made from the positions chosen by the subject, and this will be described in the next paragraph. For the colour weak and colour blind it was necessary first to readjust the slides so that the

subject continued the test from the most commonly chosen positions for the slides.

After this adjustment, if necessary, the next step was to declare to the subject that the right-hand image would be altered in colour until he noticed the change and named it correctly. If he was colour blind an incorrect name sometimes had to be accepted, as " red " for green, or " orange " for red. After this the slide was moved in the other direction to measure the threshold to the other side. The direction of movement was taken at random to red or green first, with successive subjects. Then the filters were changed for the yellow and blue pair and these were used in exactly the same way. Sometimes the order was reversed. The scale readings, noted down at the time of doing the test, were measurements of the subject's choice of the yellow mixture at first (for red and green) and of the colourless mixture (for yellow and blue), and then of the ranges into red and green or yellow and blue which he was just unable to distinguish from that of yellow or grey. Thus the matching range, or double differential threshold, is found readily, and the deviation is found by comparison with the mean position chosen by the group. It was intended to carry out the same set of tests for other colours : orange and blue-green, yellow-green and violet, and green and purple or magenta, but the technique proved to be unsatisfactory for reasons which will be explained, and, after a few subjects had been tested with the five pairs of filters, all except the red-green and yellow-blue pairs were set aside. Then a short experimental series of 50 men and 51 women were tested to complete the work on this particular test, so that the general results of such a technique could be studied satisfactorily.

There are several objections to the " paired colour-filter test, " as described here, but even so it was a far quicker and more efficient test of colour vision for normal, colour weak, deviant, anomalous and colour-blind subjects than any test known at the time. The " four-colour test " to be described in a later chapter is, however, decidedly better. The first objection to the " paired colour-filter test " was that the colours were very polychromatic. This objection might have been overcome by using the Ilford Monochromatic filters, but the other two objections made it seem better to set up a different experiment for their use.

The second objection was the latitude which the technique gave the subject in finding the neutral yellow and grey positions. This latitude proved greater than expected. Each subject was in a position to choose his own standard yellow against which to match the red-

green variable pair, and the standard grey against which to match the yellow-blue variable. After one or two subjects from the rotating disks test had been re-tested with the paired colour filters, it was seen that, while all anomalous subjects would be found without doubt by their great deviations, yet some deviant subjects might take so much latitude as to make their own deviations almost as great. This was more marked in the yellow-blue than in the red-green test : in other words, the technique had the unfortunate effect of unduly increasing the scatter of deviations by the introduction of random " errors ". Of course, it cannot be true that the standard sodium yellow of the traditional Rayleigh Equation is identical for all subjects; it must change for the yellow-weak, but the paired colour-filter test gave the subject too much freedom of choice.

The third objection was the amount of time taken in finding the positions of the standard yellow and grey for each subject individually. If the test had been continued this difficulty could have been overcome by starting each subject at the most frequently chosen neutral positions, once these mean positions had been chosen for the population. In view of the second objection, however, the test was abandoned, but it will be useful to review the results obtained with it as they are illuminating in certain ways.

Subjects of the Experiment

The paired colour-filter test was carried out on 50 men and 51 women. Thirty-two of the men were civilians, and these included three colour blind and one green anomalous who had been tested before with the rotating disks, and three red-green blind subjects who had not been tested before. In addition to the civilians, there were 15 members of an Anti-Aircraft battery in Scotland, who were tested in a dark room on the gun emplacement by kind permission of the Commander.

The 51 women subjects included 17 civilians and 34 women members of the same Anti-Aircraft battery. Of these 34 A.T.S. women seven were " spotters ". Their work was to lie on their backs in deck chairs for two-hour spells looking out for hostile aircraft. For this work they wore slightly smoked spectacles. They were specially brought forward for the test because it was thought that their colour vision might possibly be affected by staring at the blue sky and yellow or white clouds. The test was done in May 1943 at a time when there was much bright sunshine. Their results were compared with those of the remaining 44 women subjects.

DEVIATIONS AND COLOUR WEAKNESSES

The first problem to be studied was that of the frequency with which deviations from the normal mid-matching point in the red-green and yellow-blue tests occurred. This was dealt with as before by grouping the subjects according to multiples of the standard deviation (sigma). The whole group of 88 men and women, excluding the six colour-blind men and the seven women " spotters ", were taken together, and the mean neutral positions for the red-green and the yellow-blue tests were calculated, together with the corresponding standard deviations of the distributions of colour matching deviations about these means. The second problem was about the distribution of matching ranges in the two tests. As in the rotating disks test, these were strongly skewed, and they were tabulated in multiples of the modal range, which was one millimetre on the scale reading. As explained in the discussion of the rotating disks experiment, these methods of dealing with the quantitative results are much more satisfactory than methods involving ratios of red to green or logarithms of ratios.

Table 24 shows that 36 men fall into the normal class for the red-green test, 4 are deviants and one is an extreme deviant on the red side, 2 are deviants on the green side, while one of the 44 men

TABLE 24

RED-GREEN DEVIATIONS IN THE PAIRED FILTER TEST, GROUPED IN
MULTIPLES OF THE STANDARD DEVIATION

	"Normal": Less than 1 × sigma	*"Deviant"*: 1 × sigma or more but less than 2 × sigma		*"Extreme Deviant"*: 2 × sigma or more but less than 3 × sigma, including the green anomalous man*		*Totals*
	18·5-21 mm.	17-18 mm. RED	21·5-22·5 mm. GREEN	15·5-16·5 mm. RED	23-24 mm. GREEN	
Normal Men ..	36	4	2	1	1*	44
R.G. Blind Men	5	1	0	0	0	6
Normal Women	34	5	4	1	0	44
Women "Spotters"	7	0	0	0	0	7

THE " PAIRED COLOUR-FILTER TEST "falls outside the limits of the normal curve. The most extreme green deviant is a green anomalous subject in the rotating disks experiment. It would appear to be a fault of the paired filters test that he is within the deviant class in it, and is not effectively distinguished from ordinary deviants. The extreme red deviant man might be classed as red anomalous by mistake, but in the rotating disks, Ishihara and other tests it was clear that he was not, and this was additional evidence that the paired filters test was unable to discriminate the anomalous clearly.

The red-green blind subjects do not show any strong deviations in the red-green test. While the one protanope had a normal red-green equation, the red-green blind subject who shows a red deviation is a deuteranope. This again indicates the falsity of classifying these subjects into " red " and " green " blind groups and using the Rayleigh Equation as a test for such a grouping.

The distribution for women in this test is similar to that for men, and all " spotters " are in the central position. Thus, out of a total of 88 subjects 11 would be classed as red deviant and 7 as green deviant, and apart from the colour-blind men there is no sex difference to be found.

Table 25 shows similar distributions for the yellow-blue test. In this the actual measurements on the scale of the instrument are considerably greater than in the red-green test, but this may have been due in part to the fact that the colours used were more poly-

TABLE 25

YELLOW-BLUE DEVIATIONS IN THE PAIRED COLOUR FILTERS TEST, GROUPED IN MULTIPLES OF THE STANDARD DEVIATION

	"Normal": less than 1 × sigma	"Deviant": 1 × sigma or more but less than 2 × sigma		"Extreme Deviant": 2 × sigma or more but less than 3 × sigma		Totals
	20-24 mm.	24·5-26·5 mm. YELLOW	17·5-19·5 mm. BLUE	27-29 mm. YELLOW	15-17 mm. BLUE	
Normal Men ..	27	6	6	5	0	44
R.G. Blind Men ..	1	1	1	0	3	6
Normal Women ..	29	4	9	2	0	44
Women "Spotters"	5	0	1	1	0	7

chromatic than the red and green, and that they therefore tended to form grey over a fairly large range of mixtures. However, by grouping in multiples of the standard deviation and not in terms of ratios, we make the groups comparable with those in the red-green test. It is found that 27 men were normal, 11 were yellow and 6 blue deviants which corresponds to the normal curve. Of the women the distribution is much the same and no sex difference is found. The red-green blind men, strangely enough, are much more scattered here than in the red-green test, and half of them are strongly blue deviant, while only one is yellow deviant. This is exactly the opposite of what would be expected on the Young-Helmholtz or Ladd-Franklin theories, on which all red-green blind subjects should be yellow deviants.

Table 26 shows the red-green ranges of matching. In this the classification has been made on the basis of one millimetre units

TABLE 26

RED-GREEN RANGES IN THE PAIRED COLOUR-FILTER TEST

Range in mm.	1	2	3	4	5	6	14	18	21	22	23	36	Totals
Normal Men	3	23	10	5	2	1	0	0	0	0	0	0	44
R.G. Blind Men	0	0	0	0	0	0	1	1	1	1	1	1	6
Normal Women	3	24	14	1	2	0	0	0	0	0	0	0	44
Women "Spotters"	0	2	4	1	0	0	0	0	0	0	0	0	7

because no fractions of a millimetre were used in making the observations. Those who are normal have a range of 3 mm. or less, and those with ranges of 4 mm. or more may be considered as colour weak, using twice the modal range as the level at which colour weakness may be supposed to begin, as in the rotating disks test. This classification gives 37/44 men normal in range and 7 colour-weak men, and the colour weak are not necessarily deviants. The colour blind are extremely weak, having ranges between 14 and 36 mm. The distribution for women is a trifle less extreme, apart from the colour-blind men, and the "spotters" tend to be weaker than the normal women.

It is of great importance that the colour-blind men fall far beyond the limit of ranges of the most extreme of the colour weak. This is strong evidence that, so far as range is concerned, they are a separate group in the population. In this experiment, no subject was found

in the group of colour-weak subjects who might have been suspected of colour blindness, and there is a wide gap, amounting to six millimetres of the scale reading, separating the colour blind from the colour weak. The subject who was green anomalous had a range of 3 mm. and was not colour weak in this test. This confirms the view that the anomalous subjects are quite distinct from the colour blind.

TABLE 27

YELLOW-BLUE RANGES IN THE PAIRED COLOUR-FILTER TEST

Range in mm.	1	2	3	4	5	6	7	8	9	10	11	12	13	24	Totals
Normal Men ..	0	10	9	8	8	1	1	1	0	3	1	2	0	0	44
R.G. Blind Men ..	0	1	1	0	0	0	0	0	0	1	1	1	0	1	6
Normal Women ..	2	11	11	8	8	2	0	1	0	0	0	0	1	0	44
Women "Spotters"	0	0	1	3	1	0	0	1	1	0	0	0	0	0	7

The ranges for the yellow-blue test are shown in Table 27. These are similar to the red-green ranges, except that there is a greater scatter. Thus men or women with ranges of five millimetres or less will be classed as normal in range, while those with six millimetres or more will be classed as yellow-blue weak. It is interesting that the red-green blind men are more scattered in yellow-blue than in red-green ranges. One of them, who did the rotating disks test, is almost yellow-blue blind, having a range of 24 mm. in the paired filters test, and other tests on him suggest that this is a fair result. He has an extreme degree of red-green blindness of the photerythrous type, and is also moderately yellow-blue blind. It is, however, unusual for great yellow weakness to go with red-green blindness. The " spotters " seem to show greater weaknesses in yellow and blue than in red and green ranges.

From these results it became clear that in the " paired colour filter test " there was at least the possibility of a method of measuring colour-vision variations more efficiently than by any test in ordinary use. Objections to it and difficulties in its application have been mentioned, but, even as it stood, it would be better than the lantern test, wools, beads or pseudo-isochromatic tables, could be applied to normal as well as to colour-blind subjects, and was certainly more standardised and easier to apply. It also showed that all four colours, red, green, yellow and blue, must be tested if we are to make an efficient examination of a given individual's colour vision. Perhaps the most serious single objection to the paired colour filters test

was its failure to discriminate between anomalous and deviant subjects, and in the next chapters improved forms of colorimeter or anomaloscope tests will be described.

DIAGRAMS

Diagram VIII shows the results of fifty men subjects who did the paired colour-filter test in red and green, including six red-green blind and one green anomalous subject. The one protanope is marked " P ". Each individual result is represented by a horizontal
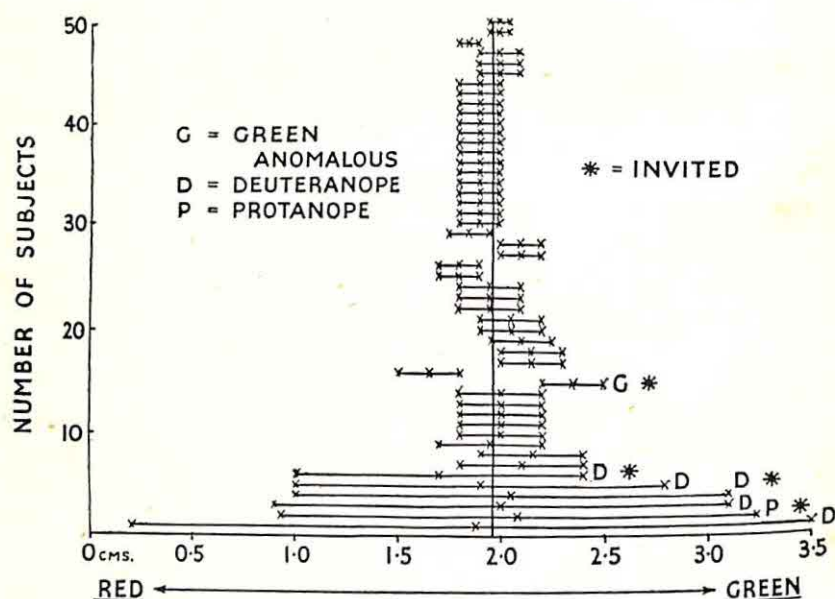
Diagram VIII. Paired Colour Filters Test : 50 Men

line which starts at the red end from the point at which the subject just began to match the standard and variable, and ends at the point at which he just ceased to make that match. Thus the ranges of matching are shown by the lengths of the lines, and the deviations by the mid-points of those lines on the red-green scale. It will be seen that the majority of subjects have small ranges and deviations. Those who have considerable deviations but small ranges are deviants (together with one green anomalous subject), while those with moderately large ranges which include the average mid matching point are colour weak. Those with small deviations and extremely large ranges are red-green blind. It so happens that none of these six red-green

blind subjects was found wholly by chance in this sample of individuals, but all were previously known to be defectives. However, in fifty men about three or four colour-blind individuals might be expected by chance in a large series of samples, and so the column of normal, deviant and colour weak above the six red-green blind subjects should be about twice as high without being any wider. This fully confirms the finding of the rotating disks experiment that the red-green blind tend to form a distinct group within the population. The anomalous do not form a link between the general population and the colour blind.

Diagram IX. Paired Colour Filters Test : 50 Men
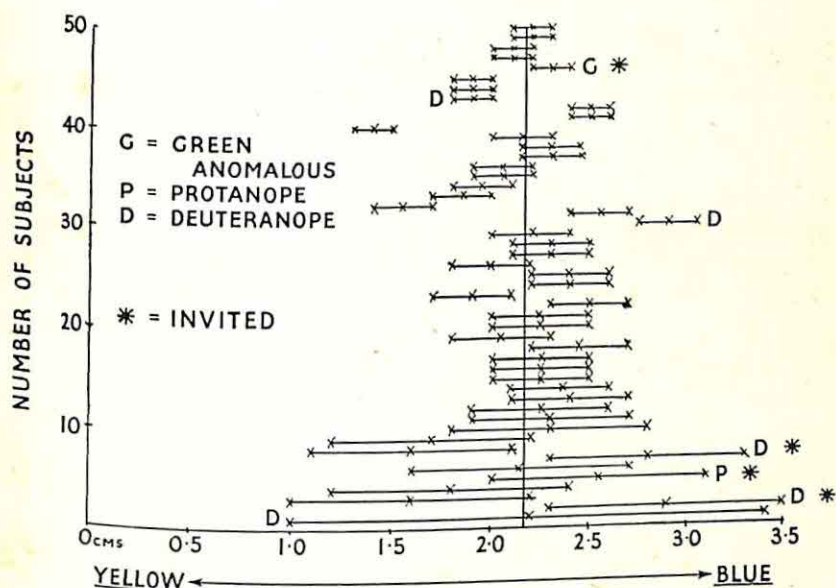
Diagram X shows similar results for the fifty-one women who also did the experiment. The general shape of the diagram is similar to that for the men, if the colour-blind men are excluded.

Diagram IX shows the yellow-blue results for the fifty men subjects, and the red-green blind are marked accordingly among them. There is a striking difference between Diagrams VIII and IX. The yellow-blue results are far more scattered although the ranges measured are not generally greater. Of course it is exceedingly difficult to make a direct comparison, and to judge yellow and blue in terms of red and green, but a far larger number of subjects have rejected the normal mid-matching point in yellow and blue than in green and red. It will be seen that four of the red-green blind

subjects are near the bottom of the diagram because they are among the weakest, but two are near the top and are among the most sensitive to yellow and blue.

Diagram XI shows the yellow-blue results for the fifty-one women subjects. They are if anything perhaps less scattered than those of
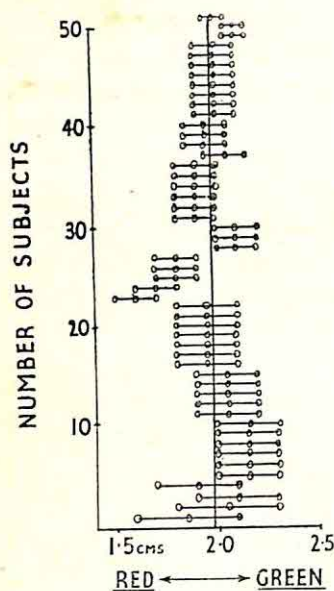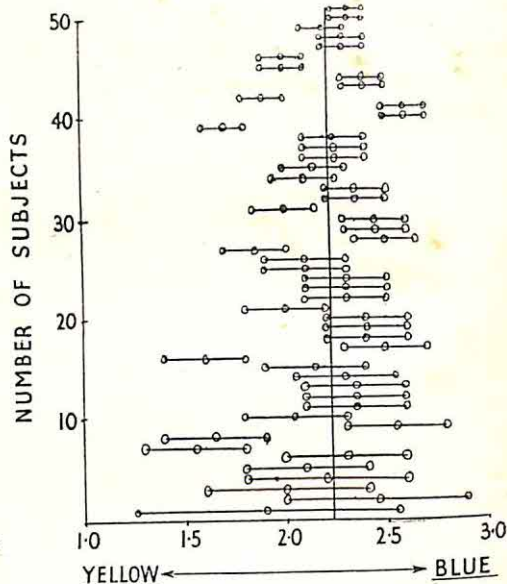
Diagram X.   Diagram XI.
Paired Colour Filters Test :   51 Women

the men, but on the whole they are much the same. For men the mean positions spread between 1.4 and 2.8 cms. on the scale, and for women they spread between 1.55 and 2.6 cms.

It is probably important to avoid misunderstanding by pointing out that there is no simple relationship between the position of a subject on the red-green diagram and his or her position on the diagram for yellow and blue. A subject might be at the top of one and at the bottom of the other, because there is no correlation between red-green and yellow-blue defects.

STATISTICAL DIFFERENCES

It is often supposed that men, excluding the colour blind and anomalous subjects, have inferior colour vision on the average to women. In the rotating disks test it was found that men showed a possible tendency to be more scattered in terms of mid-points, but

women, corresponding to the presence of about 13% who are hetero-zygous for red-green blindness, tended to have larger ranges in red and green than men. In the paired colour-filters test the mean differ-ence between men and women for mid-points was 0.20 mm., and the standard error of this difference was 0.24 mm. In order that such a difference should have been significant, for a group of 91 individuals, the standard error should have been as low as 0.077 mm., and there is not the slightest possibility of the observed difference being regarded as significantly different from zero. Similarly the mean difference in deviations between men and women for the yellow-blue test was 0.70 mm., and its standard error was 0.47 mm. Again, the ob-served difference is not significant. For red-green ranges the sex difference is almost negligible in this test, as it is for yellow and blue, though there is a slight tendency for men to be more scattered. This experiment therefore fails to support the finding of the rotating disks experiment, that more women are inclined to be red-green weak than men, excluding colour blinds, but in a sample of 51 subjects it may be that very few of the heterozygous women were included. In addition, the paired colour-filters test is probably less discriminating than the rotating disks test, for reasons already explained.

More satisfactory comparisons may possibly be made in terms of " colour weaknesses " as calculated for correlations. Thus colour weakness is a combined measure of the deviation and range taken together, as explained in Chapter II, and is usually negative except where the normal mid-matching point is completely rejected, as by anomalous subjects, and then one of the " weaknesses " of the given pair of colours will be positive. Table 28 shows the mean colour weaknesses for 43 men and 44 women with normal, deviant or weak colour vision in the paired colour-filters test, together with their differences, standard errors of these differences and critical ratios (t=diff./S.E. diff.). Of these differences only that for blue

TABLE 28

MEAN COLOUR WEAKNESSES IN THE PAIRED FILTERS TEST, WITH DIFFERENCES AND S.E.'s FOR MEN AND WOMEN

	43 *Men*	44 *Women*	*Diff. of Means*	*S.E. Diff.*	" *t* "
Red	1·3 mm.	1·4 mm.	0·1 mm.	0·11 mm.	0·91
Green	1·3 mm.	1·2 mm.	0·1 mm.	0·13 mm.	0·77
Yellow	2·3 mm.	2·0 mm.	0·3 mm.	0·25 mm.	1·20
Blue	2·4 mm.	1·8 mm.	0·6 mm.	0·25 mm.	2·40

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approaches significance and it has a probability of between 5% and 2%, so that it is not convincing.

Table 29 shows the mean colour weaknesses, differences and standard errors of differences for 43 men and six colour-blind men. Here it will be seen that for red the colour-blind men are 9.7 times as weak and for green about 9.5 times as weak as the normal men, while for yellow and blue the contrast is much less marked. The differences for red and for green are well beyond the most stringent level for statistical significance, while the difference for blue is not significant, and that for yellow has a probability of between 2% and 5% and is not convincing. These standard errors of differences were estimated by Student's method for small samples.

<div align="center">TABLE 29</div>

DIFFERENCES OF MEANS FOR COLOUR WEAKNESS BETWEEN NORMAL MEN AND RED-GREEN BLIND MEN IN THE PAIRED COLOUR-FILTERS TEST

	43 Men	6 R-G Blind Men	Diff. of Means	Estimated S.E. Diff.	"t"
Red	1·3 mm.	11·3 mm.	10·0 mm.	1·6 mm.	6·25
Green	1·3 mm.	11·1 mm.	9·8 mm.	0·9 mm.	10·09
Yellow	2·3 mm.	6·1 mm.	3·8 mm.	1·6 mm.	2·38
Blue	2·4 mm.	4·5 mm.	2·1 mm.	1·7 mm.	1·24

It is also possible to compare the red-green blind men with the remainder of the group in terms of the mean deviation. For the red-green test the difference in means of deviations between these groups was 0.1 mm, with a standard error of 2.65 mm. For the yellow blue test it was 0.47 mm, and its standard error was 0.59 mm. Neither of these differences is significant. It is clear therefore that normal and colour-blind men do not differ significantly in deviations either in the red-green or in the yellow-blue test, but they differ very greatly in ranges of matches in the red-green test, though not in ranges for yellow and blue. It is to be concluded that the weakness in red and green of the colour blind does not affect yellow.

AIRCRAFT " SPOTTERS "

The Commander of an Anti-Aircraft Battery wished to test the hypothesis that staring at the blue sky for two-hour periods in looking for hostile aircraft might have a bad effect on the colour vision of the women " spotters ". It was explained that a hostile (or other) aircraft would look like a grey or faintly yellow speck against the

blue sky or against the white or yellowish clouds. Any diminution in sensitivity to the differences between blue, grey and yellow as a result of looking at the sky might reduce the ability to distinguish such intruders. The seven "spotters" in the battery were accordingly tested and their results were compared with those of the other women. The " spotters " were actually on duty at the time and were called from their deck chairs on the gun emplacement to do the tests. The mean differences in deviation between them and the other women for the red-green test was 0.4 mm., and its standard error was 0.22 mm. For the yellow-blue test the difference was 1.1 mm. and its standard error was 0.6 mm. These differences and standard errors give critical ratios of 1/1.82 for red-green and 1/1.83 for yellow-blue. Such critical ratios correspond to a probability that 10% of similar experiments would produce this result by chance alone. This gives very slender support to the hypothesis that deviations in either test were affected by staring at the sky. For the red-green test the median range for the non-" spotters " was rather less than 2.5 mm., and in the yellow-blue test less than 3.0 mm. It is not possible to use the ordinary methods involving the standard error for comparing these ranges because they are too strongly skewed. The Chi-squared technique cannot be satisfactorily applied either, because the number of " spotters " was too small. However, there is another method which may be applied to this problem. If we divide the " spotters " into those above and those below the median range for normal subjects, in the red-green and the yellow-blue tests, we can say that there are probably six above and one below for red and green, and seven above and none below for yellow and blue. We may then calculate the probability that such a distribution could have been obtained by chance by use of the formula Standard Deviation $=\sqrt{N}pq$, where N is the number of subjects, and p and q are the respective chances of being above or below the median and are in this case both equal to one half. The standard deviation for seven subjects with equal chances of being in either of these two categories is therefore $\sqrt{7 \times \frac{1}{2} \times \frac{1}{2}} = 1.32$ approx. For the red-green test the seven subjects are divided into 6 and 1, giving an observed deviation of ±2.5, which is 1.89 × sigma, while for the yellow-blue test the observed deviation, in the same way, is ± 3.5, which is 2.65 × sigma. The result for the red-green test shows that in 6% of such experiments as big a difference would be obtained by chance alone, while the result for the yellow-blue test has a probability of less than 1% and must be regarded as significant. These results serve to indicate that the colour vision of " spotters " may be weakened in

yellow and blue but not to any extent in red and green by staring at the sky. Since the sky is chiefly blue, with white and yellow clouds, this result accords with expectation, and if a larger sample of " spotters " could have been tested no doubt a much more striking result would have been obtained. Hence there is little doubt that the ability of " spotters " to detect hostile aircraft was to some extent impaired by their method of working.

Correlations Between Colour Weaknesses

The next problems to be considered are about the extent to which variations in sensitivity to the four colours tested were related to each other. The most important point was the possibility of a connection between variations in yellow on the one hand and in red and green on the other, because this was of special interest in connection with the Young-Helmholtz and Ladd-Franklin colour vision theories. The colour weaknesses, or variations in sensitivity, were calculated on the principles explained in the chapter dealing with the rotating disks experiment, because the problem was similar although the techniques of the experiments were somewhat different. Since the colour-blind subjects do not fall into the same group for statistical purposes as the other subjects, their colour weaknesses were intercorrelated separately.

TABLE 30

INTERCORRELATIONS BETWEEN COLOUR WEAKNESSES IN THE PAIRED COLOUR-FILTERS TEST

	44 *Men*	51 *Women*
Red with Green	—·70	—·72
Red with Yellow	+·17	+·21
Red with Blue	—·13	—·18
Green with Yellow	+·03	—·17
Green with Blue	+·02	+·05
Blue with Yellow	—·58	—·61

Table 30 shows the correlations for the subjects other than the colour blind. These intercorrelations are all far below even the most lenient level for statistical significance, with the exception of those between red and green and between yellow and blue. The significant correlations are about the same size and are negative. They indicate that the four colours tested are strongly related inversely in pairs, red with green and yellow with blue, but such

intermediate relationships as those of red or green with yellow are not significantly greater than zero. It might be objected by a critic of the technique that these large negative correlations could be due at least in part to the special technical weaknesses of the paired filters test. Each subject chose his own standard, and, although there was much conformity about these choices on the average, they did tend to give a greater scatter than would have been obtained if an invariable standard had been used for everybody. Such scatter effects, however, could not possibly give rise to increases in the correlation coefficient, either positive or negative, but must always tend to reduce a correlation, unless they were such as to have the opposite effect on two colours correlated. This they did have, for every accidental deviation of the red-green match to the red side would make the "weakness" for red more positive, and that for green more negative than it would have been without this change. The opposite effect would tend to be produced by accidental deviations to the green side, and yellow and blue would be subject to similar influences. In this experiment, therefore, a part of the markedly negative relationship between red and green and between yellow and blue must be attributed to random errors in the method of measurement. In later chapters, however, it will be shown that these pairs of colours still tend to be negatively correlated, whatever technique is employed.

The inter-correlations for the six red-green blind subjects are shown in Table 31. For a group so small as six subjects none is

TABLE 31

INTER-CORRELATIONS FOR SIX RED-GREEN BLIND MEN IN THE PAIRED FILTERS TEST

Six Red-Green Blind Men

Red and Green	+ ·63
Red and Yellow	+ ·40
Red and Blue	+ ·08
Yellow and Green	+ ·36
Green and Blue	+ ·30
Blue and Yellow	+ ·26

significantly different from zero, but it is interesting that red and green are now positively correlated and so are yellow and blue, which, of course, would be expected on a four-colour theory of the Hering type, but not on a three-colour theory. The correlations between red and yellow and green and yellow, which would be expected to be

the highest of all on a three-colour theory, are not as high as that between red and green, which would on such a theory be expected to be very low.

INDIVIDUAL SUBJECTS

One subject was a very red-green blind man of the photerythrous class. In addition to the red-green and yellow-blue tests in the paired colour-filters experiment, he did precisely similar tests in which violet with yellow-green, and purple with green, were the colour pairs. These additional tests were also done by a woman with excellent colour vision. Their results are compared in Table 32. The mid-point and half-range in each of the four tests are shown in millimetres of scale reading, the full range being, of course, twice that shown after the plus-or-minus sign.

TABLE 32

MID-POINTS AND HALF-RANGES FOR A RED-GREEN BLIND MAN AND A NORMAL WOMAN IN THE PAIRED FILTERS TEST

Mid-Point and Half-Range : in Millimetres

Subject	Red-Green	Yellow-Blue	Violet-Y-Green	Purple-Gr.
Woman (Normal)	21 ± 0.5	23 ± 0.5	$25 \pm .20$	22 ± 0.5
Man (Deuteranope)	16 ± 9.0	19 ± 0.1	28 ± 2.0	24 ± 2.0

From this table it is evident that the red-green defect for the deuteranope did not affect any of the other colours to an appreciable extent in comparison with the normal. This test for eight colours was not continued, because a better method was soon discovered, and this will be described in a later chapter where numerous results of a similar kind will be discussed.

Another subject, who was a physiologist, knew that he had a great difficulty with all colorimetric physiological work in which yellows were involved, but he was aware that he could pass the Ishihara Test easily. He had been forced to give up colorimetric work because he found that he could be as much as 30% out in successive observations without knowing it. When he did the paired filters test he started by calling the blue spot " signal green " when it was fully saturated. In the yellow-blue test he then proved to have a moderate weakness in both colours, but failed to be convinced that his colour vision was unusual. Another subject who had similar

weaknesses in blue and yellow, also called the blue spot " green ". A third subject had a large blue-yellow range, but it was in his case coupled with a very large blue deviation, so that he was not weak in yellow. He was a little disconcerted when the blue defect was pointed out to him, and admitted that he had known of it as a school boy when he tried to paint in water colours. He also called the blue spot "green". He read the Ishihara Plates without the least difficulty, but the blue-green plates in Stilling's Tables he could not read at all, though he could read the blue-yellow ones easily. Another gave similar results in the tests, but had not known of his defect. He also called the blue spot " green ". Dr. M. Collins, in discussing these results, pointed out that a tendency to confuse blues and greens is the commonest of all colour weaknesses. On Edridge-Green's theory green and blue are distinguished first by the trichromics, in whom other colours, such as orange and violet are greatly impaired, but it is clear that all the blue-yellow weak subjects here described are normal in red and green, and it is better to explain their weaknesses on a four-colour theory than on Edridge-Green's system in which the distinction between green and blue cannot be lost until indigo, violet, orange and red are all affected. A further subject had a very marked range in yellow and blue, but with a big yellow deviation so that he was not at all blue-weak. The yellow spot he called " white ", but he did not call the blue spot " green ". He had no difficulty with the Ishihara Test, but he had some trouble with Stilling's yellow-blue plates and found the green-blue plates very confusing.

PIGMENTATION OF THE OPTICAL SYSTEM

These observations confirm the findings of the Rotating Disks Experiment, that blue-weak subjects very frequently tend to call blues with a tinge of green in them—like the blue used in the paired filters test—" green ". They see these blues as if through a slight " minus-blue " filter, and the result is that they are difficult to distinguish from greens. Similarly, yellow-weak subjects have as their characteristic error the confusion of desaturated yellows with white or light grey, not of blue with yellow, blue with green or green with yellow. They see yellows as if through a slight " minus-yellow " filter. A similar effect is produced for us in yellow lamp-light, when all yellows tend to look white. It has been said that " tritanopia " might be due to pigmentation of the transparent parts of the optical system, but it is difficult to see how pigmentation could produce such complex individual differences.

The last individual subject to be mentioned here was a boy of 7 years of age, who was brought because he was suspected of being colour blind. He proved to be very red-green blind and extremely scoterythrous, the saturated red filter being at least ten times darker for him than for normal people. He had a very big red-green range, but no appreciable deviation. In yellow and blue he also had a fairly wide range and no deviation. He was quite unable to do the Ishihara Test, and could read neither the red nor the magenta figures in the plates which are supposed to differentiate protanopes from deuteranopes. Consequently this test would have failed to decide into which of these classes to place him, though the simple measurement of the degree of darkening of the red, for him, left no possible doubt. He failed on half the Stilling blue-green plates. In Edridge-Green's bead test he made the following selections : red hole—one red bead; green hole—orange beads only; yellow hole—yellow beads only; blue hole—pink, pale blue and blueish grey beads. All the other beads he left on the tray, and he agreed to my suggestion that he had guessed at the choice of the one red bead, which was correct, basing his guess on the ground that it looked black to him while other people often called " black " objects red. At the age of three years he had said that a red painted bicycle was " black ". His parents pointed out that if he was in a certain dim light and his eyes were viewed so that they were seen by a bright reflected light the interior of the eyeball glowed red. They wondered whether there might be a red pigmentation which would account for his difficulty with red colours. This raised the interesting question whether pigmentation might possibly account for colour blindness. Two conditions are involved in the defect of an extreme protanope like this subject : one is the confusion of red with green of equal darkness, and the other is the darkening of the red. If the only defect were the darkening of the red, this might be accounted for by the interposition of a selective " minus-red " filter in the form of pigmentation of the transparent parts of the ocular system, so that only a fraction, say less than one tenth of the incident red light was transmitted. This would require a blue-green filter complementary to red, and of density not less than 1.0, according to the usual terminology, where the density is the logarithm to the base ten of the inverse of the fraction of incident light transmitted by the filter. Such a filter would look strongly blue-green by transmitted light, but it would not look red by reflected light unless the red light which it cut out were thrown back. Neither the blue-green appearance by transmitted light (after death of the subject, of course) nor the

red reflected light have been reported in general observations on protanopes. There is the further difficulty, however, that the presence of a minus-red filter of the density required to produce the darkening of the red, would not lead to the confusion of red with green of equal darkness invariably found in extreme protanopes. They are not " red-blind ", but red-green blind. Collins has pointed this out clearly,[2] and also drawn attention to the fact that Dalton, whose description of his own colour blindness in 1794 gave the name " Daltonism " to the condition, attributed his defect to the presence of a colour, probably blue, in one of the humours of his eyes, probably the vitreous humour. His description of his defect leaves no doubt that he was a protanope : " That part of the image which others call red appears to me little more than a shade, or defect of light; after that, the orange, yellow, and green seem one colour . . ." Examination of his eye after his death failed to support his theory that the defect from which he suffered was due to the presence of what we should call a minus-red filter in the vitreous or other humour or transparent part of the eye.[3] The only other subject, among 162 major red-green defectives of all types, in whom I have noticed the red glow in certain directions when light was reflected from the inside of the eyeball, was an extreme deuteranope, in whom red was, of course, not at all darkened. It seems very unlikely, therefore, that the red glow seen in the eye of the boy mentioned above was the explanation of his colour-vision defect.

This subject's maternal grandfather was also reported to be defective in exactly the same way, and, since his parents were very careful observers, there seems no reason to doubt that the grandfather was also an extreme protanope, which would confirm the view that the types of colour vision defect are inherited in characteristic form. Had he been a deuteranope they would not have observed the confusion of red with black. Had he been a slight or moderate protanope, or red or green anomalous, they would have not observed the defect at all, with the very limited opportunities of testing available to them in everyday life. The boy's father was tested and proved perfectly normal. His mother, however, had an unusually large range in red and green, and was beyond doubt heterozygous for the red-green defect of her father and son.

Turning to another matter, it is important to point out that the five subjects who were most weak in yellow in the paired colour-filters test were not correspondingly weak in red and green. This independence of variation in sensitivity to yellow is one of the most important considerations which weighs against a three-colour

theory. It is, of course, revealed by the smallness of the correlations between red and yellow and between green and yellow given previously, but perhaps it should be pointed out for the individual subjects. The most satisfactory way of regarding those subjects who have an independent yellow weakness is to think of them as having a defect in the yellow direction of the yellow-blue pair of functions in the Hering or Houstoun or other four-colour theory, though pigmentation of the optical system may be partly responsible for their condition.

Chapter 5

THE "BRIGHTNESS" TEST, AND "SPECTRUM" AND "MICRO" COLOUR-FILTERS TESTS

THESE three tests were undertaken in an attempt to face certain problems which may be explained quite briefly. Firstly, it is sometimes thought, as mentioned by Parsons,[1] in discussing Guttmann's observations on partial and "anomalous" deuteranopes, that colour-blind persons are better able to judge brightness differences than people with normal colour vision. This raises the possibility that weaknesses in colour vision might in general be correlated with ability to discriminate brightnesses. Secondly, Edridge-Green[2] has doubted that polychromatic colours are satisfactory for testing colour vision by colour-mixing techniques. Until monochromatic gelatine filters were available, however, all tests of colour vision were necessarily with polychromatic colours, except those using the spectrometer, which was Edridge-Green's main guide. Thirdly, since polychromatic colours are the rule in everyday life, it is interesting to question whether a test of colour vision using polychromatic colours will produce the same result as a monochromatic test. Fourthly, it was hoped that one of these tests might serve as a quick and reliable method of testing colour vision for general use.

These problems were, of course, coupled with the additional but familiar questions about the general nature of colour vision and its variations, but they have been explained previously and need not be repeated here.

The three tests will now be described. They were: the "Brightness" test; the monochromatic or "Spectrum" Filters test; and the polychromatic or "Micro" Filters test.

DESCRIPTION OF THE TESTS: THE "BRIGHTNESS" TEST

The test of brightness discrimination was carried out with the side-shutters of the colorimeter, the colour-filter slides being taken right out. The left shutter was set at 15 mm. and this gave a standard brightness for the left-hand spot of light. The right shutter was then set at 20 mm. and the subject, seated at $1\frac{1}{2}$ metres distance, was asked

if there was a noticeable difference in brightness between the spots. If he saw no difference, which was seldom, then the test was re-started with a bigger difference. Provided the subject saw a bright-ness difference at the start, then the test proceeded by decreasing the brightness of the right-hand spot in steps of one, two or three millimetres, according to the sensitivity of the subject, until he saw the two spots alike. Then the right spot was made darker than the left step by step until he saw the left as brighter. Finally the series was completed by reversing the same steps until the right spot became brighter again to the subject. This is the usual technique of the limiting method, with one descending and one ascending series, and more descents and ascents were added for any subjects who seemed doubtful or erratic.

The upper and lower thresholds were then determined, and the whole range or double differential threshold, within which the subject saw the two spots alike in brightness, was recorded. This is called the " brightness range " in the present chapter, and was taken as a measure of the subject's brightness discrimination. Most of the subjects found this an easy test, and the brightness range was usually established in equal halves above and below the position of objective brightness equality, namely, 15 mm. for the right-hand shutter. For some subjects there is a certain amount of difficulty, and a tendency to undershoot or overshoot the position of objectivity equality. Then the brightness range was unequally divided about the right-hand shutter reading of 15 mm. In computing the results no account was taken of this irregularity. It was sufficient to find the range within which the subject was not able to distinguish the variable from the standard under the precise conditions of the test. Further, the test was not repeated with the right and left positions of variable and standard reversed, because two other tests were done at the same sitting and no subject could be expected to do this kind of work reliably for more than half an hour at a time.

The " Spectrum " Filters Test

This test used the Ilford monochromatic or " spectrum " filters: red (608), yellow (606), green (604) and blue (602) in essentially the same way as that in which the red, yellow, green and blue paper disks were used in the rotating disks experiment. The approximate transmission bands of these filters are given in Table 33, and full details of their physical properties may be found in the Ilford Colour Filter Booklet.[3] These filters are, of course, not perfectly

monochromatic, as may be seen readily by examining with a pocket spectroscope the light they transmit. Each filter transmits a very small amount of light of the colours immediately adjoining its colour. Thus the red filter transmits a small amount of orange,

TABLE 33

TRANSMISSION BANDS OF ILFORD SPECTRUM FILTERS

	Red (608)	Yellow (606)	Green (604)	Blue (602)
Ångstrom	6250—	5600—	5000—	4450—
Units	end of spectrum	6100	5450	4950

the yellow a small amount of orange and of yellow-green, the green a small amount of yellow-green and of blue-green, and the blue a small amount of blue-green and of violet. For all practical purposes they may be regarded as satisfactorily monochromatic. In this respect they are comparable with the colours obtained in an ordinary spectrometer, and no coloured inks, dyes or lantern filters commonly in use can compete with them.

In the colorimeter it is possible to control the brightnesses of the two spots by means of the side shutters, but for this test it was also necessary to be able to desaturate the standard yellow with grey when required, or to make a standard grey for the yellow-blue test without employing the side shutters, which would be necessary for brightness control. For these purposes it was found satisfactory to use Ilford standard neutral filters. These filters transmit all the component rays of white light in the same proportions as those in which they fall upon the filter, but with diminished intensity, and therefore are neutral in colour. Details of their properties may be found in the Ilford Colour Filter Booklet.[3]

Preliminary tests showed that in matching spectrum red mixed with spectrum green against spectrum yellow a small amount of desaturation of the yellow would be necessary. This was done with the neutral filter of density 1.02. This filter cuts down the incident light to one tenth. The density is the logarith to the base ten of the reciprocal of the transmission value of the filter. The transmission value is the ratio of the luminous flux transmitted by the filter to the luminous flux incident upon it.

The spectrum blue and yellow filters are complementary, and, in certain proportion, match the white light of a daylight blue lamp precisely. These filters, however, cut the incident light by a large proportion, and, in order to dim the standard spot to their

brightness the left shutter would have to be closed to about 2.5 cm. This would force the experimenter to employ only the very edges of the lenses on the left of the apparatus, and would make the brightness control on the left side very inefficient in consequence. In addition, it would force all brightness control to be carried out with the minute movements of the shutter which could not be read on the scale. To overcome these difficulties two Ilford neutral filters, density 1.02 and 2.02 respectively, were used together in the left slide for the yellow-blue test. The 1.02 density filter cuts incident light down to one tenth and the 2.02 density filter cuts it down to one hundredth. Thus the slide could be used to fix the brightness of the left spot at a standard level between one tenth and one hundredth of the incident light, whatever level was suitable, and the left shutter was then free for fine adjustments—which is exactly equivalent to dividing the shutter scale readings (without the neutral filters) by a constant falling anywhere desired between 10 and 100.

In setting up the Spectrum Filters test there were two separate sub-tests : firstly red and green were matched against the yellow standard (desaturated with grey), and secondly yellow and blue were matched against grey. The red-green test was carried out with the red filter below and the green above it in the right-hand slide, and with the neutral filter (1.02) below and the yellow above it in the left slide. The left slide was then set at a scale reading of 30 mm., determined by preliminary trials as a suitably small desaturation with grey —5 parts of grey to 30 of yellow. It was found in preliminary tests that the right slide was likely to produce a yellow mixture to match the monochromatic yellow on the left at a scale reading of about 21 mm. The exact matching point and range of matches was then determined for each subject individually. It was found that the left or standard light spot was usually too bright, which was convenient and intended. The technique was then as follows : The subject, who had just finished the brightness test, was seated at $1\frac{1}{2}$ metres from the apparatus. The filters were arranged as described above, and the right slide was set at about 16 or 17 mm. The subject was told that the experiment was to match the two spots for both colour and brightness, and that no colour match would be accepted unless brightnesses were equal. If he showed any hesitation or difficulty in distinguishing hue and brightness, then the brightnesses were deliberately altered to prove to him that the distinction could be made. Next he was asked if there was a brightness difference at the starting positions mentioned above. Almost invariably the left spot was brighter, and was then altered until it seemed to him the same in

brightness as the right. Next he was asked if there was a colour difference. Usually the right spot looked redder, pinker or more orange than the left, which was slightly green. The Ilford Spectrum Yellow filter is very often described as green or greenish yellow when compared with a pink. The right slide was then moved in steps of one millimetre, and the subject was asked to describe any colour difference he saw at each step. Usually he failed to see a colour difference at about 20, 21 or 22 mm., sometimes at 19 or at 23, or at any or all of these points. The test was continued until the spot looked greener. The test was then repeated, starting from the green side and proceeding back to the red side again. Very rarely with normal subjects (but always with protanopes) it was necessary to adjust the brightness with the left shutter as the test proceeded. Thus the whole technique was an application of that used for the rotating disks to the new apparatus.

For red-green blind subjects a different procedure was necessary, and it was useful to make sure by a preliminary test whether or not the subject was colour blind. Such a preliminary test is easily done with the colorimeter by setting the right slide at several widely separated positions, such as 5, 10, 15, 20, 25, and 30 mm., and, after a brightness adjustment in each case, asking whether there is a colour difference. If the subject hesitates over a match at any of these points except 20 mm., or if he requires great darkening of the standard at 5 or 10 mm., then it is almost certain that he is red-green blind. Any hesitation over a red-green match which is very exceptional is suspicious, and the subject must on no account be given any hint of his possible error, but he must be carefully tested until the full range of his red-green matches has been determined.

If the subject is suspected of an exceptional red-green defect, then the red-green spectrum filters test should be started at 0 mm., where the right spot is saturated red, and here a brightness match will show whether he is a protanope or a deuteranope. Then a series of colour matches at five millimetre intervals can be made, brightness being controlled carefully, to gain a general idea of his range and deviation, and detailed tests may be made at the limits of his range to determine them accurately. In this way the exact nature and extent of his red-green defect will be found. It is a mistake to give the colour blind the benefit of the doubt when they hesitate over a colour match which the normal would reject out of hand.

For the yellow-blue test the arrangement was : right slide, blue below, yellow above; left slide, neutral filters, 2·02 below, 1·02 above, at 30 mm. scale reading.

The " Micro " Filters Test

This was an attempt, which was not successful, to make a specially simple, quick and efficient test with polychromatic colour filters. The reasons why it was unsuccessful will be explained later. It was called the " Micro Filters Test " because three out of the four filters used in it were from the Ilford " Micro " filter series. The four filters were : red (205), yellow (110 or Micro number 4), green (405 or Micro number 3) and blue (303 or Micro number 2), all in the Ilford series of colour filters. They were chosen as a result of preliminary trials. Their transmission bands are shown in Table 34, and full details of their physical properties will be found in the Ilford Colour Filter Booklet.[3] From the table it is clear that the red filter transmits both red and orange; the yellow transmits part of the green, all the yellow-green, yellow, orange and red; the green transmits blue-green, green, yellow-green and yellow; the blue transmits blue, blue-green, green and yellow-green, together with a small amount of red. These filters, having wide transmission bands, are polychromatic and very bright.

Table 34

Transmission Bands of Ilford Colour Filters (Polychromatic)

	Red (205)	Yellow (110)	Green (405)	Blue (303)
Ångstrom Units	6050 to end of the Spectrum	5100 to red end of Spectrum	4900— 6000 and a little red	4300—5600 and a very little red

The experiment was set up in such a way that all four filters were always in place in the colorimeter, and one subject after another could be tested without changing them at all. The yellow and blue filters were placed in the left slide, yellow above and blue below, while the red and green filters were placed in the right slide, red below and green above. The subject, who had just finished the " Spectrum " filters test, was instructed that the new test involved matching of the two spots both for colour and for brightness as before, a brightness match always being a pre-requisite for a colour match. Then the test was made with the two spots either red and blue, red and yellow, green and blue or green and yellow. It was thought that the variety of starting positions would be an advantage because it would prevent subjects from instructing each other in the expected routine of testing. The subject was asked to describe and name the

colour differences seen and the slides were then adjusted to reduce those differences until a colour match was obtained. The brightness of the left-hand spot had to be adjusted so that a brightness match was maintained throughout. When the neutral position of brightness and colour equality was found in this way, each slide was varied in the direction of one colour after the other and back again to the neutral place, to obtain a measure of the threshold for that colour. The subject stated when a colour difference was seen and explained what it was.

Initially this test had the faults of the paired filters test, because it involved complex trial and error adjustments without a fixed standard either for the red-green or for the yellow-blue pair. As soon as enough subjects had been tested to establish the usual matching point, the test was always started at this point and readjusted to suit the individual subject. Even then, however, it proved to be a troublesome test, especially with colour-blind subjects, although the results to be quoted later suggest that it was more reliable with them than with other subjects. The colour naming of the red-green blind is often so unexpected that it gives the tester little indication what change to make in the adjustment of the filters. More criticisms will be given later, when the results are discussed, but the advantages of simplicity and freedom from rigid technical routine, which this test seemed to offer, were far outweighed by the complexities of the adjustments required and the liberty of choice given to the subjects, which introduced unnecessary random errors.

RESULTS OF THE TESTS : THE " BRIGHTNESS " TEST

The brightness test was carried out on 21 normal men, 12 normal women, 7 red-green blind men and 1 green anomalous man: 41 subjects in all. With the exception of one moderate deuteranope and one normal man all these subjects also did the " Micro " filters test. All 41 of them did the " Spectrum " filters test as well. The mean brightness range for men and women together, excluding the red-green defectives, was 2.63 mm., and for the red-green blind men it was 3.86 mm. For the 12 women it was 2.5 mm., and for normal men it was 2.82. The standard errors of all these means were calculated, and the standard errors of the differences between the various pairs of means were found. There were no significant differences between any of these groups.

Thus it was concluded that the experiment showed that normal men, normal women and red-green defective men do not differ in

ability to discriminate brightness differences, and the hypothesis that colour-blind subjects are speciallly good at brightness judgments was not supported at all. The green anomalous man was the most accurate in brightness discrimination, but one of the protanopes was least accurate. A man with normal red-green vision, who was exceptionally weak in yellow and blue was particularly good at brightness judgments.

In order to test more fully the hypothesis that brightness discrimination might be connected with colour weakness, correlations were calculated between brightness ranges and red-green ranges in the " Spectrum " filters test, and also between brightness ranges and yellow-blue ranges in the same test. These are shown in Table 35.

TABLE 35

CORRELATIONS BETWEEN BRIGHTNESS DISCRIMINATION AND COLOUR WEAKNESS

Correlations between :	33 normals	8 R-G defectives
Brightness and R-G weakness	+·13	+·14
Brightness and Y-B weakness	+·33	−·13

They are all below the usual significance level, though that between brightness discrimination and yellow-blue weakness suggests a small relationship. From this it was concluded that there is no relation between colour weakness and ability for brightness discrimination either in normal or in red-green defective subjects. The results were so definite that it did not seem worth while to continue the brightness tests further. The supposition of the exceptional ability of colour-blind subjects to discriminate brightness differences is probably a false inference made from their habitual exploitation of brightness differences to aid them in estimates of colour differences which they find difficult and normal people find easy. The evidence of this test, however, suggests that they are not any better than normal people at judging brightness differences, in spite of this special practice. The brightness thresholds for the 41 subjects who did this experiment are shown in Diagram XII.

THE " SPECTRUM " FILTERS TEST

This test was considered satisfactory and was continued, after the " Micro " filters and brightness tests had been discontinued,

and it formed part of the next series of experiments, which will be discussed in the following chapter. At present it will be useful to consider the results in so far as they apply to the group of subjects who also did the brightness and " Micro " filters tests.
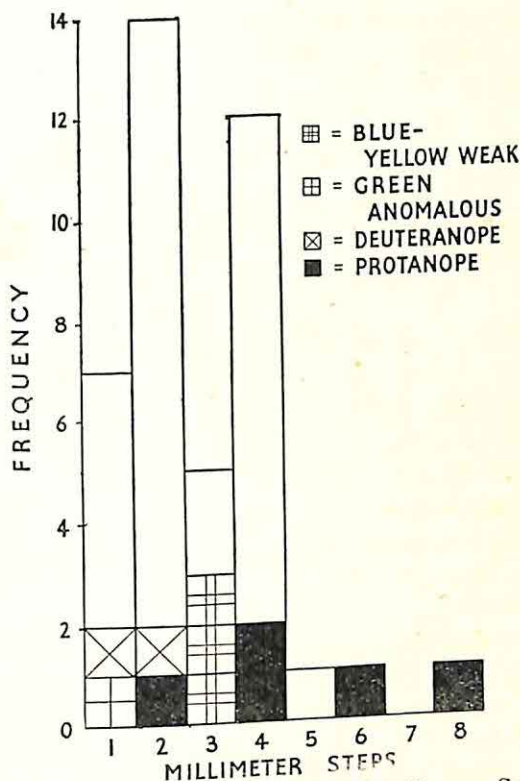
Diagram XII. Brightness Test: Thresholds: 41 Subjects

Table 36 shows the distributions of red-green matching points for 21 men, 12 women and 8 red-green defectives, one of whom was green anomalous. These results are given, as before, in terms of multiples of sigma (standard deviation) for the whole group of 41 subjects. They show that there is no difference between men and women in deviations, and no deviants were found in this small group of subjects, except among the colour blind and anomalous. Five of the seven red-green blind were protanopes, but only one of them shows a marked red deviation. He accepted the normal match with ease, however, and cannot be considered red anomalous. The seventh red-green blind man, who was a deuteranope, and who showed a large green deviation, almost accepted the normal match

TABLE 36

RED-GREEN MATCHING POINTS IN THE "SPECTRUM" FILTERS TEST, IN MULTIPLES OF SIGMA (STANDARD DEVIATION)

	Less than 2 × sigma	2 × sigma or more, but less than 3 × sigma		3 × sigma or more, including the one anomalous man*		Totals
		RED	GREEN	RED	GREEN	
Normal Men	21	o	o	o	1*	22
R-G Blind Men	5	1	1	o	o	7
Normal Women	12	o	o	o	o	12

and cannot be regarded as green anomalous. One subject, who is beyond doubt green anomalous, had a much larger green deviation, more than 5 × sigma, and a very small range, so that there is no possibility of confusing him with the deuteranopes. Hence the "Spectrum" filters test clearly distinguished the anomalous and supported the conclusions of the rotating disks test that red or green deviation in the colour blind has little or no connection with darkening of the red end of the spectrum.

Table 37 shows the distribution of yellow-blue matching points for the same group of subjects in the "Spectrum" filters test. One man, who had a big blue deviation, has been mentioned in the discussion of the paired filters test as a very blue-weak subject. One red-green blind man, who had an even larger blue deviation in the "Spectrum" filters test, also showed this in the paired colour

TABLE 37

YELLOW-BLUE MATCHING POINTS IN "SPECTRUM" FILTERS TEST

	Less than 2 × sigma	2 × sigma or more, but less than 3 × sigma		3 × sigma or more		Totals
		YELLOW	BLUE	YELLOW	BLUE	
Normal Men	21	o	1	o	o	22
R-G Blind Men	6	o	o	o	1	7
Normal Women	12	o	o	o	o	12

filters test. He is a moderate deuteranope with a very marked deviation in blue in addition.

Table 38 shows the distribution of ranges of red-green matches for the " Spectrum " filters test, and Table 39 shows the corresponding distribution of yellow-blue matching ranges. Those subjects

TABLE 38

MATCHING RANGES IN THE "SPECTRUM" FILTERS TEST—RED AND GREEN

Range in mm.	·5	1	2	3	4	5	6	7	14	20	25	28	33	Totals
Normal Men (Anom.*)	1	11	9	1*	0	0	0	0	0	0	0	0	0	22
R-G Blind Men	0	0	0	0	0	0	0	1	1	1	1	1	2	7
Normal Women (Heterozygous*)	4	2	4	1*	1*	0	0	0	0	0	0	0	0	12

who have the largest ranges in the one do not necessarily have the largest in the other. From these tables it is clear that the ranges in red and green and in yellow and blue for men and women are not very different, apart from the colour-blind men. Two women who were known to be heterozygous for red-green blindness, because their fathers were colour blind, had the largest red-green ranges. The

TABLE 39

MATCHING RANGES IN THE "SPECTRUM" FILTERS TEST—YELLOW AND BLUE

Range in mm.	·5	1	2	3	4	5	6	7	8	9	10	11	12	20	Totals
Normal Men	1	3	2	3	4	2	3	1	1	1	0	0	0	1	22
R-G Blind Men	0	0	3	2	1	0	0	0	1	0	0	0	0	0	7
Normal Women	2	4	0	2	1	0	1	0	0	1	0	0	1	0	12

seven red-green blind men have vastly greater ranges in the red-green test than the normals, and these results, taken with Tables 36 and 37, showing deviations, confirm the view that it is range rather than deviation which distinguishes the colour blind. In Table 39 one subject who had a range of 20 mm., is almost yellow-blue blind, while those

who had ranges of 5 mm. or more may be classed as yellow-blue weak. Similarly, in Table 38, those with ranges of 2 mm. or more, excluding the colour blind, may be classed as red-green weak. No red-green weak subjects are found with ranges of more than 4 mm., and no colour blind with ranges of less than 7 mm. This gap corresponds to the critical level for the Ishihara Test : the red-green blind fail and the red-green weak pass, but the anomalous also fail.

Table 40 shows the mean colour weaknesses, as calculated for correlational purposes, for the thirty-two normal men and women and for the seven red-green blind men who did the "Spectrum" filters test, together with the differences of these means, the standard errors of these differences and critical ratios. It will be observed that the

TABLE 40

DIFFERENCES BETWEEN COLOUR WEAKNESSES IN NORMAL AND RED-GREEN BLIND SUBJECTS IN THE "SPECTRUM" FILTERS TEST

	32 Normal Men and Women	7 Colour Blind Men	Diff. of Means	S.E. diff.	" t "
Red	0·53mm.	10·40mm.	9·87mm.	·75mm.	13·25
Green	0·59mm.	12·20mm.	11·61mm.	·79mm.	14·69
Yellow	1·44mm.	1·57mm.	0·13mm.	·58mm.	0·22
Blue	2·89mm.	1·86mm.	1·03mm.	·65mm.	1·59

differences for red and green are very great, as found before in the rotating disks and paired filters tests. Here, however, they are 19.6 times as great for red and 20.7 times as great for green in colour blind as in normal subjects, whereas in the other tests, which used polychromatic colours, the weaknesses for colour blind were in the neighbourhood of 10 times as great for these colours as in normal subjects. This difference would be explained by the fact that monochromatic colours provide a much more stringent and revealing test than polychromatic colours. Anomalous subjects are also more clearly differentiated when monochromatic colours are used. The differences shown for yellow and blue between normal and red-green blind subjects are not significantly different from zero.

Diagram XIII shows the results for 41 men and women who did the "Spectrum" filters test, including 7 red-green blind men and one green anomalous man. The men are shown by crosses and the women by circles. The general features of the diagram are similar to those of the red-green diagrams for the paired filters test. There is a very marked difference between normal and red-green blind subjects, but in this diagram the least colour-blind man has a com-

paratively narrow range. He has a strong green deviation and rejects the normal mid-matching point by a very narrow margin. He is one of the interesting subjects who are possible intermediates between colour blind and anomalous, but he could not be classed as anomalous except in error, because the truly anomalous subject, had a range of 3.0 mm., and a deviation of 6.5 mm., whereas the subject who was colour blind had a range of 7.0 mm., and a deviation of only 3.5 mm. Other green anomalous subjects will be discussed in a later chapter to show that this conclusion can be supported by further data. If,
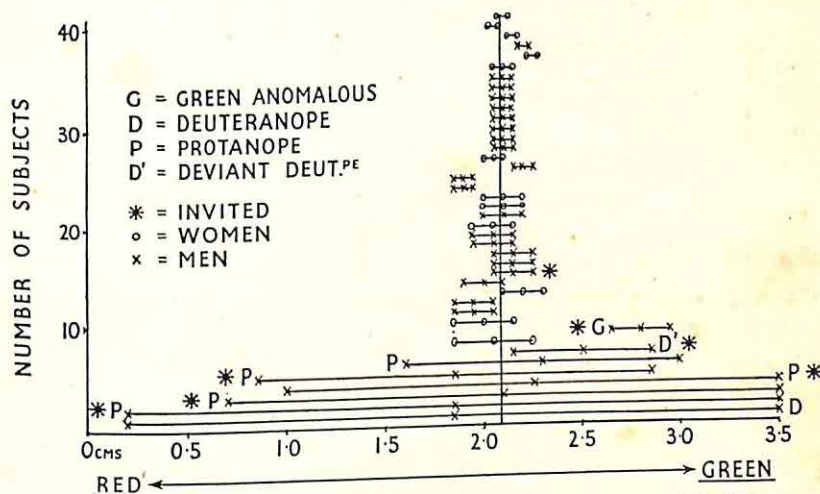
Diagram XIII.   Spectrum Colour-Filters Test : 29 Men and 12 Women

as appears, there are two separate tendencies at work, one to produce the green anomalous condition and the other to produce the condition of the deuteranope, then it would be likely that sometimes subjects should be deviant or anomalous deuteranopes. Five of the colour-blind men are marked as protanopes. Of these, three deviate mainly to the red side, one has no deviation and one deviates to the green side. Thus the present experiment supports the conclusion that protanopes may have green deviations.

Diagram XIV shows the results for the same 41 subjects in the yellow-blue test. The seven colour blind are indicated by the letters P or D (protanope or deuteranope). It will be seen that 6 of them have very small yellow-blue weaknesses, but the seventh might be described as a blue deviant. This confirms the view that yellow-blue weaknesses are not often found among the colour blind. Like the corresponding yellow-blue diagrams in the discussion of the paired filters test, this shows a much bigger scatter of mid-points

than the red-green diagram. The technique of this experiment was different, and also the filters used here were monochromatic, whereas in the paired colour-filters test they were polychromatic. The subjects are also different, and so the greater scatter of yellow-blue deviations
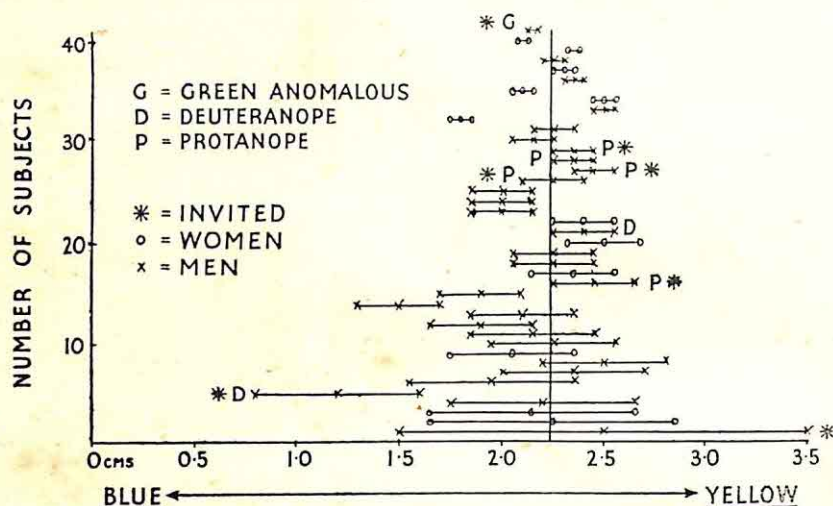
Diagram XIV.   Spectrum Colour-Filters Test : 29 Men and 12 Women

would appear to be a characteristic of colour vision and not a product of the method of testing.

Correlations were calculated between " colour weaknesses " according to the technique described in previous chapters, and between " colour weaknesses " and brightness levels for the corresponding colours. These are shown in Tables 41 and 42. It will be

TABLE 41

INTER-CORRELATIONS BETWEEN "COLOUR WEAKNESSES" IN THE "SPECTRUM FILTERS TEST"

	R-G	R-Y	R-B	G-B	G-Y	Y-B
32 normals	−·44	−·25	+·27	+·02	+·42	−·39
7 R-G blinds	+·86	+·76	−·38	−·48	+·81	−·49

TABLE 42

CORRELATIONS BETWEEN "COLOUR WEAKNESSES" AND BRIGHTNESS LEVELS IN THE "SPECTRUM" FILTERS TEST

	R-Bright	Y-Bright	G-Bright	B-Bright
32 normals	+·30	+·30	−·09	+·17
7 R-G blinds	−·17	+·20	−·46	+·26

seen that in normal subjects there is a tendency for negative correlations between red and green and between yellow and blue, while other pairs are almost uncorrelated except green and yellow. In the red-green blind subjects there are positive correlations between red and green, red and yellow and green and yellow. This suggests a confirmation of the Young-Helmholtz theory as far as red-green blind subjects are concerned, but it must be remembered that correlations may be misleading, for the actual weaknesses correlated were, in yellow and blue, not exceptional compared with normal subjects, while in red and green they were on the average about ten times as great as in normal subjects. Hence there is no real relationship between yellow weakness and either red or green weakness, when the red-green blind are compared with the normal, though the correlations
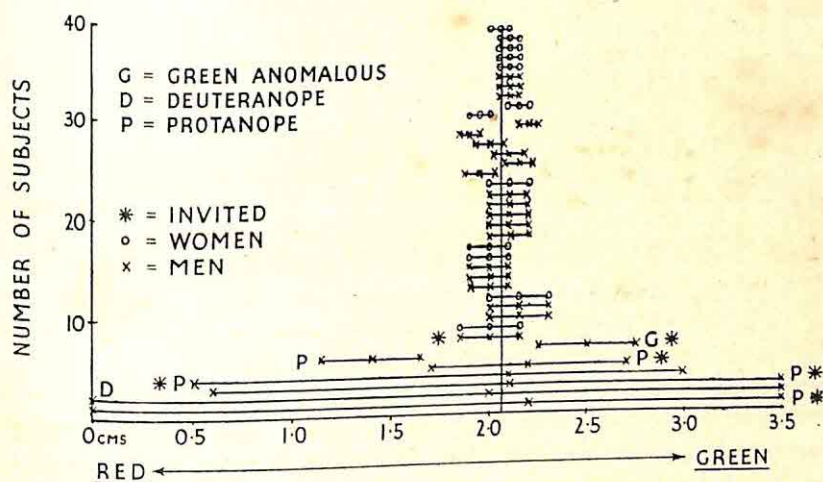
Diagram XV. " Micro " Colour-Filters Test : 27 Men and 12 Women

would suggest that these relationships are greater for the colour blind. From Table 42 it appears that colour weakness, whether in normal or colour-blind subjects, is uncorrelated with brightness levels, and this indicates that brightness level is not diminished when colour sensitivity is reduced.

THE " MICRO " FILTERS TEST

Diagrams XV and XVI show the mid-points and matching ranges for the same group of subjects (with the exception of two who did only the " Spectrum " filters test) in the " Micro " filters test. These results correspond only moderately with the results of

the " Spectrum " filters test. One subject who was extreme in the " Spectrum " filters test was only deviant in the " Micro " test. He is green anomalous. The other highest and lowest men in the one test were not correspondingly highest and lowest in the other. The same failure of correspondence holds good for the yellow-blue test. Although the red-green blind subjects were clearly picked out by both tests, there was not a high degree of consistency between the tests in their detailed results.
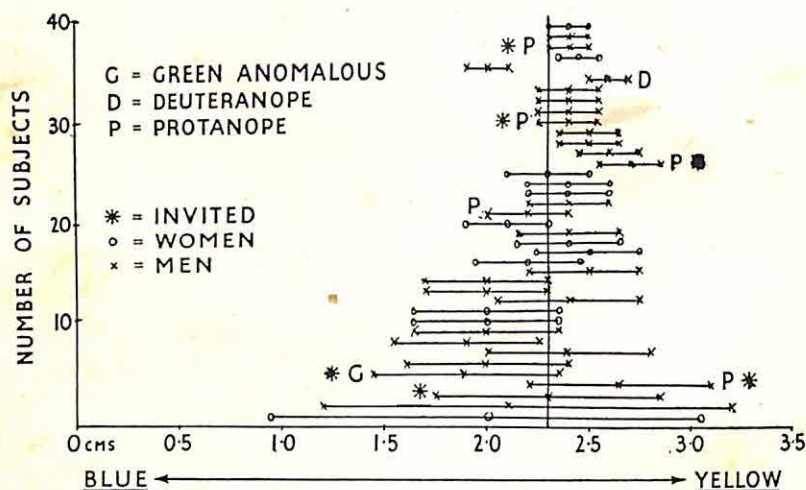
Diagram XVI. " Micro " Colour-Filters Test : 27 Men and 12 Women

Correlations between the " Spectrum " and " Micro " filters tests are given in Table 43. To be statistically significant these correlations should be as great as about 0.5 for the 32 normal subjects and about 0.9 for the six red-green blind men.

TABLE 43

CORRELATIONS BETWEEN "SPECTRUM" AND "MICRO" FILTERS TESTS, NORMAL AND COLOUR-BLIND SUBJECTS

	Red	Yellow	Green	Blue
32 normal Men and Women ..	− ·06	+ ·02	− ·20	− ·13
6 Red-Green Blind Men ..	+ ·41	− ·62	+ ·62	− ·67

None of these correlations is significant, and, in view of this and the other objections to the " Micro " filters test which have been mentioned already, detailed results of it need not be given. The average colour weakness in the " Micro " test for red-green blind subjects, however, was still about ten times as great as for normal

subjects for red and green, but not significantly different for yellow and blue. Hence it was concluded that the " Micro " test, although it distinguished red-green blind from normal subjects without difficulty, did not give satisfactory results when used to distinguish small differences between individuals, either normal or colour blind.

A short comparison of inter-correlations for colour weaknesses in the two tests will be interesting. These are shown in Table 44.

TABLE 44

INTER-CORRELATIONS FOR COLOUR WEAKNESSES IN THE "SPECTRUM" AND "MICRO" FILTER TESTS

	R-G	R-Y	R-B	G-Y	G-B	Y-B
"Spectrum" 33 normals	−·44	−·25	+·27	+·42	+·02	−·39
"Micro" 32 normals	−·43	+·71	−·30	−·36	+·43	−·36
"Spectrum" 7 R-G Blind	+·89	+·76	−·38	+·79	−·23	−·49
"Micro" 6 R-G Blind	+·79	−·27	+·89	+·22	+·71	−·47

For normal subjects the pattern of correlations is changed by use of monochromatic filters, except that the negative correlations between red and green and between yellow and blue persist, as they tend to do in all tests. The high correlation between red and yellow in the " Micro " test is certainly due to the fact that the yellow filter used in that test transmitted actually more red than the red filter. Similarly, the relatively high correlation between blue and green is due to the fact that the blue filter transmitted as much green as the green filter. Negative correlations between red and blue and between green and yellow complete the symmetrical pattern. For the " Spectrum " filters test, there are negligible correlations between red and yellow, red and blue and green and blue, while green and yellow appear to be positively correlated, and the opposite pairs, red and green and yellow and blue are negatively correlated. The positive correlation between green and yellow may be due to the fact that for many subjects the Ilford Spectrum yellow filter appears very greenish, and might represent the influence of naming rather than a characteristic of colour vision. Certainly the four filters do not appreciably overlap. For the colour-blind subjects it is interesting that the correlation between red and green is now positive for both tests, while that for yellow and blue remains negative as for normal subjects.

This clearly reflects the difference from normal subjects in their red-green vision, and the absence of difference in their yellow-blue vision. Apart from this it would not be satisfactory to draw any inferences from the other correlations for red-green blind subjects, for it is likely that the inconsistencies between the tests might be due to the inefficiency of the " Micro " filters test.

INDIVIDUAL SUBJECTS

There were seven red-green blind subjects in the " Spectrum " filters test, five of whom were invited because they were known to have red-green defects. The first, who also did the paired filters test, was a moderate deuteranope who has a large green deviation and rejected the normal mid-matching point by a very small margin. He has been discussed already. He was also a blue deviant. The second was a moderate protanope who had a strong red deviation, but was normal in yellow and blue. He had been rejected by the R.A.F. in a colour-vision test, but had. no difficulty with colours himself, though his " art teacher never agreed with him ". The third was an extreme protanope, also rejected by the R.A.F. in a colour-vision test. He had no red-green deviation. He described his difficulty in distinguishing red from dark browns, light browns from green and blue from purple. He also had difficulties with pale greens and yellows, and said that pink was " just not a colour " to him. The fourth was another extreme protanope without a red-green deviation, and he had also been rejected by the R.A.F. He confused greens and browns, reds and dark browns, and yellows and greens. He was not confident of reds under any circumstances, but had no trouble with the distinction between yellows and blues. He noticed his defect at about fifteen years of age, but never took much interest in colours. The fifth was another extreme protanope, and he had been rejected by the R.A.F. eight times. He reported sometimes actually overlooking the red traffic light altogether, thinking that it was not working. His mother's father was reported to have been colour blind, and to have confused red and green with dark and light brown respectively, and pink with pale blue. From this we should infer with some confidence that the grandfather was also a protanope, and this would give confirmatory evidence of the inheritance of the defect true to type. Had the grandfather been much less colour blind it is probable that the defect would not have been noticed in the family circle, and so we may infer that the grandfather was also an extreme defective making it probable that the defect was

inherited in magnitude as well as in type. Many readers may doubt there liability of these inferences, but as a result of careful inquiries into the manner and degree in which defects of different magnitudes and kinds are noticeable by ordinary people in daily life, it seems that the inferences may be made with considerable confidence. The next subject, another protanope, confused orange with fawn and with red, which is unusual, but this is probably explained by the fact that he had a decided weakness in yellow though not sufficient to class him as a yellow deviant. He also reported having confused red and blue trams in Glasgow, which is not unlikely in a protanope, because blue trams are very dark. His brother, his mother's sister's son and his maternal grandmother were all reported colour blind, but I was unable to make contact with the family. His mother's father was said to be normal. Such relationships would accord perfectly with the usual sex-linked scheme, however, because, if the maternal grandmother were a protanope, both her daughters would necessarily be heterozygous if she married a normal man, and both of them could have sons who were protanopes. The last colour-blind subject to be discussed here was a moderate deuteranope. He was definitely not green anomalous, but belonged to the class to be called " deviant " deuteranopes, because he had 3.5 times the normal range of matches and accepted the normal mid-matching point with ease. He reported no difficulty with colours. All these colour-blind subjects were complete and unequivocal failures on the Ishihara test.

The " Spectrum " filters test gives a reliable measure of the degree of darkening of the red end of the spectrum in protanopes, which cannot be obtained satisfactorily from tests using polychromatic papers or colour filters, because the red in polychromatic colours is somewhat diluted with other colours. It is interesting, therefore, to work out a correlation between the degree of darkening of the red and the red weakness : $r = .26$, which is, of course, far below the significance level. It is, however, so small as to suggest that there is little or no relationship between darkening of red in these protanopes and their inability to distinguish red from a yellow of equal darkness.

The series of subjects included one who was extremely yellow-blue weak without any defect in red and green. He was unable to read the blue-green figures in Stilling's Tables. He was completely unable to do colorimetric work in physiology, if yellows were involved, and often called desaturated blue-green colours " green ". He had a very large range in yellow and blue, with a yellow deviation. There was another interesting subject, who had been in Dr. R. A.

Houstoun's series, and had been told by him that she was slightly abnormal in blue-green colours, which she often called " green " when other people called them " blue ". She proved in this test to have a small blue-yellow weakness, but was normal in red and green. Another subject was rather weak in yellow and reported calling a dress " green " when her friends insisted that it was " yellow-green ". She said that her father claimed that there was no such colour as blue, but asserted that it was " just a shade of green ". As he was old and an invalid it was not possible to arrange to test him, but there can be little doubt of his being decidedly blue-yellow weak, and it seems reasonably certain that he was not red-green blind. This would suggest the hereditary nature of blue-yellow weaknesses, and confirm the hypothesis that they are not sex-linked. Another subject who was blue-yellow weak, tended to call blueish green colours " green ".

Chapter 6

THE "NINE-COLOUR" EXPERIMENT: NORMAL, DEVIANT AND COLOUR-WEAK SUBJECTS

THE main aim of this experiment was to discover how far colour vision for intermediate hues may vary with sensitivity to the primaries. It was most important to find out whether any subjects might be specifically weak in one of the intermediate colours and not in one of the primaries; for example, to find out whether any subjects might be more weak in orange and blue-green than in red and green. In addition, it was interesting to discover which of the intermediate colours was more and which less frequently weak. Blue-green was specially interesting because Houstoun suggested peacock should be taken as a primary instead of green. Violet was interesting because of the possibility that this end of the spectrum might be darkened in some subjects. Magenta was interesting because it is the complementary of green and deuteranopes are supposed to see certain purples as if colourless, since they are made up of red and blue, which are complementaries for extreme red-green defectives.

Burt[1] has pointed out that the problems of the number and relationship of primary colours might be approached by the methods of factorial analysis. The present experiment was planned with the possibility of factorial analysis in mind. Since red, green, yellow and blue were the expected primaries, so far as other tests and experiments reported in this book could indicate, it was necessary for the purposes of factorial analysis to add as many intermediates as possible, to test all these by the same technique on the same subjects, and then to intercorrelate and factorise the resulting measurements. This would be expected to show which colours tended on the average to be weakened together, from which the presence of primaries might be inferred, according to the pattern of factor loadings.

The experiment also raised other important problems. These will be dealt with fully as we proceed, but may be summarised here. They were : the fuller study of any variations of sensitivity to colours which might be due to pigmentation of the skin or racial differences, suggested by Burt[2] and Vernon[3]; the more detailed study of red-green defectives, especially in respect of the intermediate colours;

sex differences, if any, and problems of heredity; the comparison of a group of subjects who came from the Glasgow School of Art with other subjects. In this chapter the normal, deviant and colour-weak subjects will be dealt with, and the red and green anomalous and colour-blind subjects will be reserved for the next chapter.

TECHNIQUE

The " Spectrum " filters experiment was continued for red, green, yellow and blue exactly according to the technique described in Chapter V. The intermediate colours were added, and details will now be given about the way in which they were used. For the orange+blue-green sub-test the Ilford Spectrum orange filter (607) was used in the right-hand slide of the colorimeter with the Spectrum blue-green filter (603) below it. An intermediate mixture of these two colours produced a dark grey which matched the neutral filter of density 2.02 in the left slide. This slide was maintained throughout the test at zero scale reading. The orange filter was far too bright, however, in comparison with the blue-green, and had to be cut down with a neutral filter of density 1.02, which was placed in a special slot made for the purpose behind the orange filter, in such a way that it did not overlap the blue-green filter at all. Under these conditions the left-hand spot was brighter than the right, and the brightnesses were equalised by controlling the left-hand shutter. This sub-test was always carried out starting at a reading of the right-hand scale which gave a spot more blue-green than the left, then the spot was changed until it was more orange and then back until it was more blue-green again. If any difficulty arose, further series of readings were added for confirmation.

For the yellow-green+violet sub-test the Spectrum yellow-green filter (605) was used with the violet (601) below it in the right-hand slide. It was not necessary to reduce the brightness of either of these with an additional filter. At an intermediate mixture the yellow-green and violet filters produced a grey which was very faintly blueish in hue. To match this grey exactly the left-hand spot was made slightly more blue by use of the Spectrum blue filter (602), which was placed above the neutral filter of density 2.02 in the left-hand slide, and the slide set at a scale reading of 15 mm. The colour of the left-hand spot under these conditions may be described best as a faintly blueish grey. The best position was determined by preliminary experiments. This sub-test was carried out from the violet end towards yellow-green and back again to violet. In passing towards yellow-green there was a noticeable increase in brightness, and the

brightnesses of the two spots were equalised by means of the right-hand shutter, while the left shutter was always fully open, because the right-hand spot was brighter than the left, with both shutters open. For exceptional subjects, who will be discussed later, in whom the violet is darkened, the left-hand shutter had to be used.

The fifth sub-test in the series was done with magenta (501 or Micro No. 6) above and Spectrum green (604) below it in the right slide. The filters are almost complementary, and an intermediate mixture of their colours gives a grey with a very faintly blueish hue. This grey was produced with the blue filter (602) above and the neutral filter of density 2.02 below it in the left-hand slide, and set at 25 mm. scale reading instead of 15 mm. as for the yellow-green + violet test. The magenta-green sub-test was always carried out from magenta towards green and back again, the brightness of the magenta was much greater than that of the green, and brightnesses were equalised with the right-hand shutter.

The order of the five sub-tests was as follows : 1, red-green; 2, orange + blue-green; 3, yellow-blue; 4, yellow-green + violet; 5, magenta-green. All five tests could be carried out in less than half an hour with the majority of subjects, and it was an advantage that the short intervals required for changing the filters gave the subjects rest pauses of a few minutes duration. Most subjects considered the yellow-blue and yellow-green + violet sub-tests to be the most difficult, especially the latter. For all but the red-green blind, any test in which the predominant change seems to be from a reddish to a greenish colour is easier than one in which it appears to be from a yellowish to a blueish colour. Thus orange to blue-green, red to green and magenta to green all give the predominant impression of a red-green change, whereas yellow to blue and yellow-green to violet give a predominant impression of changing from yellow to blue. This greater ease of red-green tests for normal subjects is strongly reflected in the factorial analysis which will be discussed later, where the red-green factor is decidedly predominant. For certain subjects who were very blue-weak it was necessary to compensate by setting the left slide at 10 mm. instead of 15 mm. for the yellow-green + violet sub-test. This made the standard grey for that test blue enough for them but far too blue for the majority. It may be a little unfortunate that the polychromatic magenta was not paired with a polychromatic green, such as Micro No. 3 (or 404), to make the whole experiment more symmetrical, but it was thought that monochromatic colours should be used wherever possible, and no changes could be introduced after the experiment had been started.

G

SUBJECTS

The " Nine-colour " experiment was carried out on 245 subjects in all : 135 men and 110 women. A number of normal and most of the abnormal subjects also did the Ishihara Test. A proportion of the subjects were invited because of known colour-vision defects; others because of known defects of relatives; others again because they were Indians, West Africans or Jews. Each subject was classified as " dark ", " moderately dark ", " medium " or " fair ". This classification was based on hair and skin colour combined, but it was found that the four-fold classification was unsatisfactory, so the " moderately dark " were later included with the " dark " and the " medium " with the " fair ". A number of normal and abnormal subjects who had taken part in previous experiments were included in order to enable the experimenter to gain some idea of the relationship between the tests used. After excluding the colour-blind subjects and those who had been specially invited a random sample of 103 men and 86 women remained, 189 in all. One man did not do the purple-green test; so the number of men for this test was 102.

DEVIATIONS

Table 45, and Diagram XVII show the distribution of deviations for men and women in the red-green test. Four major defectives (1 woman and 3 men) have been added to this and the following diagrams in this chapter. It will be seen that no subjects in the table fall beyond the limits of ± 3 × sigma. Anomalous subjects, who are much more extreme, will be dealt with in the next chapter. Six

TABLE 45.

DISTRIBUTIONS OF MID-POINTS FOR THE RED-GREEN TEST WITH SPECTRUM FILTERS, IN TERMS OF STANDARD DEVIATION—COMPARED WITH NORMAL CURVE

	"Normal": Less than 1 × sigma	"Deviants": 1 × sigma or more but less than 2 × sigma		"Extreme Deviants": 2 × sigma or more but less than 3 × sigma		Totals
	20·5-22·5 mm.	19·5-20 mm. RED	23-23·5 mm. GREEN	18·5-19 mm. RED	24-24·5 mm. GREEN	
MEN ..	80	13	7	2	1	103
WOMEN ..	70	7	3	2	4	86
NORMAL CURVE ..	68	13·7	2·3	13·7	2·3	100

women and three men who fall in the 2—3 sigma class may be called extreme deviants. The grouping in terms of the standard deviation in this and the following tables for the other sub-tests in this experiment is approximate, because readings of less than 0.5 mm. were not made. The Chi-squared test, however, shows no significant difference between the distributions for men and for women, and that neither differs significantly from the distribution expected in a normal curve of 100 hypothetical subjects shown on the same table.

MID – POINTS

WOMEN ABOVE   ▣ = PROTANOPE
MEN BELOW   ▨ = DEUTERANOPE
IN EACH FIGURE   ▣ = RED ANOM.
   ▤ = GREEN ANOM.(♀)
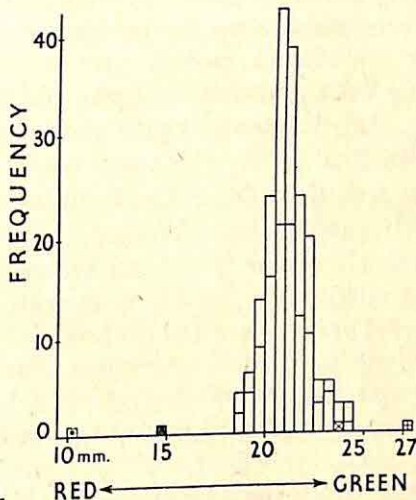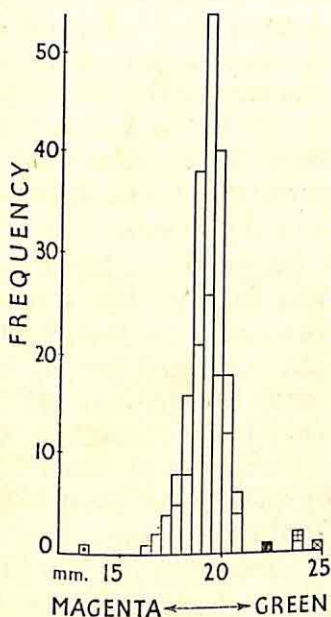
Diagram XVII. Nine-Colour Experiment : Half-Millimetre Steps. Magenta-Green : 105 Men. Red-Green : 106 Men. 87 Women in Both

More exact grouping in terms of the standard deviation would therefore not be necessary.

Most of the extreme deviants shown in this table showed peculiarities of colour vision in daily life. One of them, a Polish youth, made five mistakes in the Ishihara Test. In addition to his red deviation he had a red-green range of 5 mm., which classes him as very red-green weak as well as being an extreme deviant. He had a difficulty with Nagel's card test, and he reported that he had been

tested for the Air Force a year before and rejected. He thought his colour vision was worse then, and that it had improved as a result of rest and better food since he had escaped from German occupied Poland.

The most extreme woman red deviant was a subject with so large a range (7 mm.) as to be almost classifiable as red-green blind rather than as a deviant in the strict sense. On a second test, a month later, she had a smaller deviation and range, but this was partly due to practice in doing the test. She made seven mistakes in the Ishihara Test, and reported calling a colour " blueish rose " when other people called it " rust ", and another colour " buttercup yellow ", which was indignantly denied by her friends. Colours she calls " purple " other people call " pink ". If the colour she called " buttercup yellow " had been orange to the normal, all these peculiarities of naming would accord with her special weakness in red, although red was brighter than the normal for her. She did the Holmgren's Wool Test, and was excessively particular, which is characteristic of the colour weak and colour blind. She succeeded in passing the test, but called the standard pink skein " purple " and refused to match it with coral pinks, which apparently looked yellowish to her. This again accords with her predominantly red weakness. She reported that her paternal grandfather's brother's daughter was said to be completely colour blind, and had called a navy blue frock " pink ". This relationship would fit in with the sex-linked pattern if the paternal grandfather and his brother had both been colour blind and had both married heterozygous women, when the daughter of the one and the son of the other could have been red-green blind. Presumably the daughter was not totally colour blind, but an extreme protanope, for whom such an error as that of calling a navy blue frock " pink " would be possible. If this were the pattern or inheritance, then the subject's father must have been the colour-blind son in question. Accordingly he was invited, came to the laboratory and was tested. He had no peculiarity in red and green, but a moderate yellow-blue range. That possible pattern of inheritance was apparently ruled out, and it seemed that her defect could not have been inherited from the same line as that of her parental grandfather's niece. Accordingly it might have come from her mother's side of the family, but her mother was dead, and it was not possible to get in touch with any maternal relatives, though an aunt on her mother's side was said to be a red-green defective. Since her father was not red-green blind the subject should not have been homozygous for red-green blindness, but must, presumably, have been heterozygous.

Thus we have evidence of the magnitude of red-green defect which may sometimes be produced by the heterozygous condition in a woman.

Another point of interest is that her condition could not have been due to the interaction of two different genes, one for protanopia and the other for deuteranopia, which has been suggested as the cause of somewhat marked defects in a proportion of women. Had this been her condition, then her father must have been red-green blind, but he was normal. In Chapter X, however, it will be seen that, on the two-locus theory, a man of normal phenotype might be a double-defective in genotype, and have a defective daughter. This woman subject, though not either colour blind or anomalous according to any strict definition of these conditions, is certainly weak enough to be failed with justice in any serious test of colour vision.

One subject who almost fell into the extreme green deviant class made three mistakes on the Ishihara Test. He was also very yellow weak. His spectrometer readings are interesting in comparison with the readings for eight subjects given in Chapter I. These are shown in Table 46. The central readings for the various colours for

TABLE 46

MID SPECTROMETER READINGS FOR COLOURS BY SUBJECT M191 COMPARED WITH THE AVERAGE FOR EIGHT OTHER SUBJECTS— IN ÅNGSTROM UNITS

Subj.	Red	Orange	Yellow	Y-Grn.	Green	B-Gr.	Blue	Violet	"Purple"
M191	6500	6200	6100	6000	5770	5530	4950	4750	4260
Mean for 8	6550	6125	5880	5485	5390	5365	4810	4540	—

this subject are given above and the average central readings for eight other subjects below. It will be seen that there is a distinct tendency for yellow, yellow-green and green to be shifted towards the red end of the spectrum, and a corresponding tendency for purple to be included in the end of the part usually called violet, though the positions of red and blue are unchanged. This corresponds well with his weaknesses in green and yellow observed in the colorimeter experiment. Blue and blue-green encroach upon the diminished green, yellow and yellow-green, while there is a tendency for red to encroach upon their complementaries, especially violet, from the other side of the colour circle, so that he called the extreme violet part of the spectrum "purple". He smoked fifteen cigarettes a day, and said that he had had a bad night fire-watching before

doing the tests. The tests were repeated four months later, and this time his green deviation was greater, putting him in the extreme deviant class, so it seems unlikely that the weakness can have been due to a sleepless night. There was no evidence suggesting a sex-linked defect in his case, but it is almost impossible to be confident of its absence, because his mother was not available for testing, and even if she had been tested she might have given an indecisive result.

The deviations in the orange+blue-green test are shown in Table 47, grouped in the usual manner, and in Diagram XVIII. There
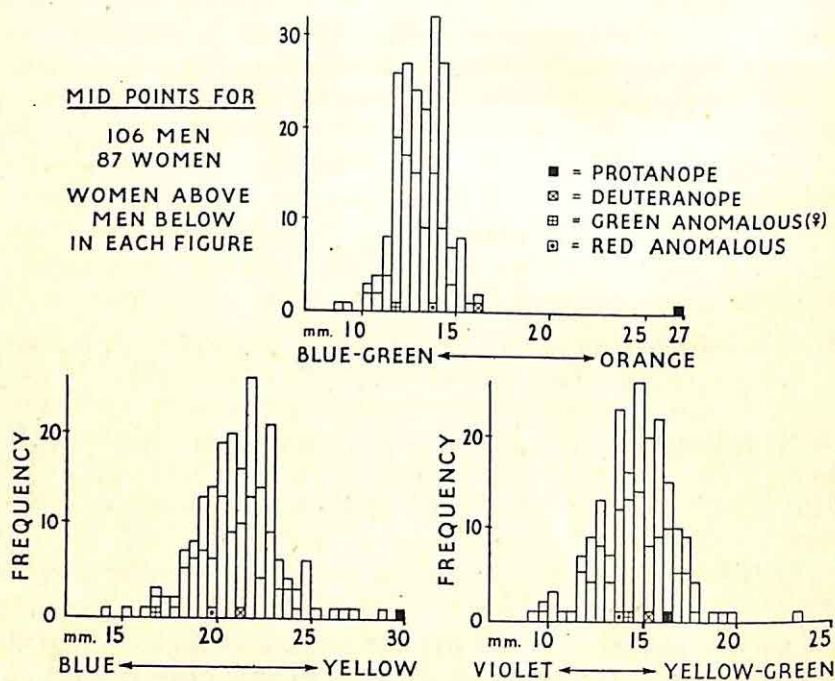
Diagram XVIII.   Nine-Colour Experiment: Half-Millimetre Steps

were only three extreme deviants in this test, one man and one woman on the blue-green side and one woman on the orange side. Again there are no sex differences. The extreme subjects are interesting. The first had a very big range in the yellow-blue test, and he rejected the normal orange+blue-green match, though his red-green vision was normal. It would appear that his yellow-blue weakness did not affect orange, but did affect blue-green. The second also rejected the normal orange+blue-green match, and was an Indian woman who had a green extreme deviation. Apparently her weakness in green

affected blue-green. The third was the woman who had an extreme deviation in green and so big a red-green range as to be almost colour blind. She was discussed in the previous group of subjects. She has

TABLE 47

DEVIATIONS IN THE ORANGE+BLUE-GREEN TEST GROUPED IN MULTIPLES OF THE STANDARD DEVIATION

	"Normal": Less than 1 × sigma	*"Deviant":* 1 or more but less than 2 × sigma		*"Extreme Deviant":* 2 or more but less than 3 × sigma		*Totals*
	12-14·5 mm.	15-16 mm. ORANGE	10·5-11·5 mm. B-GREEN	16·5-17·5 mm. ORANGE	9-10 mm. B-GREEN	
MEN ..	82	12	8	0	1	103
WOMEN	73	4	7	1	1	86

also a very big range in the orange+blue-green test. It is clear that her red-green range affects her orange+blue-green range, and the red deviation is reproduced as an orange deviation in the present test. Her yellow-blue vision is normal, although her red-green defect appears again in a large yellow-green deviation in the violet+yellow-green test, and as a large range in the green-purple test.

In Table 48 and Diagram XVIII the deviations for the blue-yellow test are shown. The standard deviation (sigma) for women is not significantly less than that for men, but it seemed more convenient to group them separately here. There are two blue and two

TABLE 48

BLUE-YELLOW DEVIATIONS IN MULTIPLES OF THE STANDARD DEVIATION; MEN AND WOMEN GROUPED SEPARATELY

	"Normal": Less than 1 × sigma	*"Deviant":* 1 or more but below 2 × sigma		*"Extreme Deviant":* 2 or more but below 3 × sigma		*More than 3 × sigma*	*Totals*
		BLUE	YELLOW	BLUE	YELLOW		
MEN	19·5-23·5 mm. 72	17-19 mm. 15	24-26 mm. 10	14-16·5 mm. 2	26·5-28 mm. 3	29 mm. 1	103
WOMEN	20-23 mm. 66	18·5-19·5 mm. 10	23·5-24·5 mm. 6	17-18 mm. 2	25-26 mm. 1	14·5 mm. 1	86

yellow extreme deviant men, but they would be beyond the 3 × sigma limit for women, whereas the two blue and one yellow extreme deviant women would be deviants if they were men. There is one man beyond the + 3 × sigma limit on the yellow side, and one woman beyond the −3 × sigma limit on the blue side. The first of these has already been discussed at some length as a green deviant, and his spectrometer readings were given in Table 46. In the yellow-blue test he has an exceptionally large deviation, and although his range is also very large, it does not overlap the normal mid-matching point. He had no difficulty with the yellow-blue figures in Stilling's Tables, but found the blue-green figures very difficult. The second subject was a woman art student, about whom no other information is available, except that she is normal in red and green. In yellow and blue she has an extreme deviation to the blue side, and is one of the rare subjects who might almost be classed as blue anomalous, because her range is very small. Blue was not darkened for her. However, her blue deviation was not so extreme as the red and green deviations of the subjects to be classed as red and green anomalous, and, since the intermediates in blue can be found, whereas in red and green they are not to be found, the expression blue anomalous will not be used.

In the violet+yellow-green test, the results of which are shown in Table 49 and Diagram XVIII, the men are again apparently more scattered than the women, though there is not a statistically significant difference between their standard deviations (sigmas). There are five violet and three yellow-green extreme deviants among the

TABLE 49

DEVIATIONS IN THE VIOLET+YELLOW-GREEN TEST GROUPED IN MULTIPLES OF THE STANDARD DEVIATION; MEN AND WOMEN GROUPED SEPARATELY

	"Normal": Less than 1 × sigma	"Deviant": 1 or more but below 2 × sigma		"Extreme Deviant": 2 or more but below 3 × sigma		More than 3 × sigma Y-Green	Totals
		Violet	Y-Green	Violet	Y-Green		
Men	13-16 mm. 74	11-12·5 mm. 10	17-18·5 mm. 11	8-10·5 mm. 5	19-21·5 mm. 2	23·5 mm. 1	103
Women	13·5-16·5 mm. 59	12-13 mm. 12	17-18 mm. 12	10-11·5 mm. 2	18·6-20 mm. 1	— —	89

men, and two violet and two yellow-green deviants among the women. These subjects are interesting. The most extreme yellow-green deviant man was a West African (Yoruba) who had a large but not very exceptional yellow-blue range, and he was a yellow deviant. He called the test spot " green ". The first woman yellow-green deviant showed no other peculiarity, but the second was exceptionally yellow-blue weak, with darkened violet, and her defects had appeared in the rotating disks test.

The five violet deviant men all rejected the normal match, and one of them was a green deviant who had exceptional yellow weakness. He called both the spectrum blue and violet " purple ", which accorded with his naming the extreme violet end of the spectrum " purple ", as mentioned above, and he had a tendency to call the spectrum yellow-green filter " blue " in comparison with the violet. He is probably a type of subject Edridge-Green would class as having a general colour weakness.[5] Another was almost a deviant in blue and red, and his extreme deviation in violet may be viewed as the summed effect of the other two weaknesses. He was also a purple deviant. His colour naming exactly accorded with these weaknesses : he called the spectrum green filter " blue ", the blue " purple ", the yellow " orange ", the blue-green " blue ", the orange " brown " and the purple filter " red ". This is an interesting example showing how the colour naming of a defective subject may accord perfectly with his own colour perception and is not the result of chance errors as often supposed. Violet was not at all darkened for him, but was markedly weakened; red and blue were rather less weakened than violet. Purple in consequence looked red and violet looked blue; green and yellow, which were not at all weakened, invaded and were confused with blue and orange respectively. In the beads test he placed red beads correctly, but he put yellow-green beads in the green hole along with green beads; yellow beads he placed correctly, but he classed orange as a kind of yellow, and in the blue hole he included blue-green, blue and dark grey beads. He objected strongly when his peculiarities were pointed out and discussed with him after the tests. This was on December 31st, 1943, and he had agreed to do the test about 9 p.m. while fire-watching, with many protests on account of the pressing nature of his studies, which he wanted to pursue, but he kept the experimenter until after mid-night disputing the results of the tests, and departed for bed only when it was agreed to submit them to a third party for arbitration. Needless to say the third party was never consulted. It was a very cordial discussion and an unusual way of spending New Year's Eve.

G*

Of the remaining three men who were violet deviants, two also showed marked blue-yellow defects, one having an exceptional range and the other being a blue deviant. The third showed a moderate degree of blue deviation together with a moderate green deviation. One had the violet very darkened.

There were two women with extreme violet deviations. The first, who was almost a green deviant, had a very large range in blue and yellow without any deviation. The second accepted the normal violet+yellow-green matching point and had a very large range in blue and yellow without deviation. She had very darkened violet. It is an interesting observation that extreme violet deviation occurs sometimes with and sometimes without darkening of the violet. This is a serious problem for the Young-Helmholtz theory, on which it should always correspond with darkened violet. A parallel difficulty is found with red deviations, which do not necessarily correspond to darkening of the red end of the spectrum, as they should on a three-colour theory.

Table 50 and Diagram XVII show the distributions of deviations for men and women in the purple-green test. The women seem to

TABLE 50

DEVIATIONS IN THE PURPLE-GREEN TEST IN MULTIPLES OF THE STANDARD DEVIATION : MEN AND WOMEN GROUPED SEPARATELY

	"Normal": Less than 1 × sigma	"Deviant": 1 or more but less than 2 × sigma		"Extreme Deviant": 2 or more but less than 3 × sigma		More than 3 sigma	Totals
		PURPLE 17·5-18 mm.	GREEN 20·5-21 mm.	PURPLE 16·5-17 mm.	GREEN 21·5-22 mm.	GREEN 24 mm.	
MEN	18·5-20 mm. 73	9	16	3	0	1	102
WOMEN	19-20mm. 67	18·5mm. 8	20·5mm. 6	18mm. 3	21mm. 2	— —	86

be less scattered than the men, but the difference of standard deviations (sigmas) is not statistically significant. The extreme deviant women would be merely deviants if they were men.

The six extreme purple deviants, three men and three women, show that deviation in purple can arise from weaknesses either in blue and violet, in red alone or in red and blue together. This accords exactly with expectations based on the principles of colour mixing. In general the study of the deviations shows that weaknesses in any of the

intermediate colours, orange, yellow-green, blue-green, violet or purple, always correspond with weaknesses in one or more of the four primaries, red, yellow, green and blue. According to the Young-Helmholtz theory yellow would be one of the intermediates, and weaknesses in it would be expected to accord with weaknesses in red and green, but are found to be independent of them. Weaknesses in yellow are related more frequently to blue weaknesses than to red or green. Orange and yellow-green, however, vary in relation to red, yellow and green, not to red and green alone, and the evidence from deviations tends decidedly to support four rather than three primaries.

There is an important characteristic of the series of tests taken together. Table 51 shows the standard deviations of all five tests for men and women separately : for both sexes it tends to increase

TABLE 51

STANDARD DEVIATIONS OF THE FIVE TESTS FOR MEN AND WOMEN

Test :	Red-Green	Orange+B-Green	Yellow-Blue	Yellow-G+Violet	Purple-Green
SIGMA (mm.) MEN	1·03	1·30	2·29	2·11	1·02
WOMEN	1·06	1·18	1·72	1·70	0·64

consistently as the test-axis is moved round the colour circle from red-green towards yellow-blue and then decreases again as the axis returns towards red-green from the other side. None of the differences between the standard deviations of men and woman are significant, though there is a fairly consistent tendency for women to have lower standard deviations than men. This would support the suggestion that men are more scattered in mid-points than women. The difference between the red-green and the yellow-blue tests is almost significant for men, with a probability of about 2%, but not for women, while that between the yellow-blue and purple-green tests is significant for women but barely significant for men (p=2% again). Hence the tendency for standard deviations to increase from the red-green test to the yellow-blue test, and to decrease again in returning to the red-green test the other way, is statistically significant when the whole group of 103 men and 86 women are taken together. This fits in well with other evidence showing that red-green contrasts are more sharply defined than yellow-blue contrasts, and with the fact that red-green tests are much easier to set up and to carry out on normal subjects than yellow-blue tests, though it is the other way round with the colour blind.

MATCHING RANGES

The ranges of matching in the red-green test are shown in Table 52 and Diagram XIX. The modal range for men is 0.5 mm. and for women 1.0 mm. If the subjects with a range of 3 mm. and more are

TABLE 52

MATCHES RANGING IN THE RED-GREEN TEST

Range in mm.	0·5	1·0	2·0	3·0	4·0	5·0	6·0	7·0	Totals
MEN	38	31	17	13	0	4	0	0	103
WOMEN	21	40	17	2	4	0	1	2	86

grouped together, Chi-squared shows that there is a decidedly significant difference between the distributions for men and women. The main difference is that more men are specially sensitive. It is also true that more men are less sensitive, but this contributes an insignificant amount to Chi-squared, relatively to the other difference. This confirms the result of the rotating disks test : in red-green matches women are less particular than men, but men are probably more scattered than women. The extreme subjects all had slight difficulties with colours in daily life.

In Table 53 and Diagram XIX the ranges in the orange and blue-green test are shown. Here again, the modal range for women

TABLE 53

ORANGE+BLUE-GREEN RANGES FOR MEN AND WOMEN

Range in mm.	0·5	1·0	2·0	3·0	4·0	5·0	6·0	7·0	8·0	Totals
MEN	13	40	28	13	5	1	2	0	1	103
WOMEN	12	22	24	15	10	2	1	0	0	86

appears to be slightly larger than for men, but there is not a statistically significant difference. Of the seven weakest subjects, all but one had very large yellow-blue or red-green ranges. The remaining subject had red, purple and blue deviations. The red and blue deviations in combination might account for the purple deviation and for the orange+blue-green range.

Table 54 and Diagram XX show the distribution of matching ranges in the yellow-blue test for men and women. Here the ranges have been grouped in 2-millimetre units up to 11.0 mm., and then

in larger units, in order to reduce the length of the table. It is interesting to compare this table with Table 52, which shows the
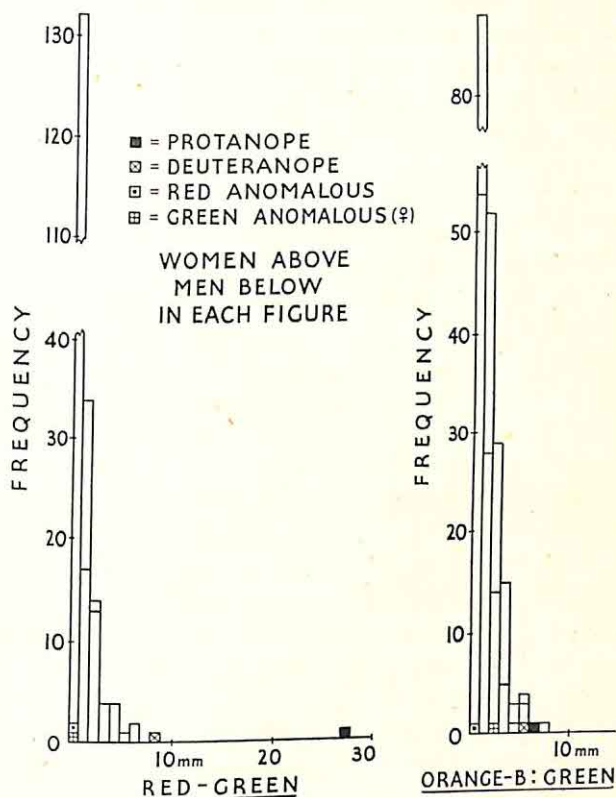
Diagram XIX.   Nine-Colour Experiment.   Matching Ranges :   106 Men; 87 Women : Millimetre Steps

red-green ranges. The spread in yellow and blue is more than three times as great as in red and green. If the red-green blind subjects were included in Table 52, then its spread would be greater than that of the yellow-blue table, but there would be a large gap between the ordinary subjects and the red-green blind, whereas in Table 54 there

TABLE 54

YELLOW-BLUE RANGES : MEN AND WOMEN SUBJECTS

Range in mm.	0·5- 1·0	2·0- 3·0	4·0- 5·0	6·0- 7·0	8·0- 9·0	10·0- 11·0	12·0- 15·0	16·0- 19·0	20·0- 25·0	Totals
MEN	8	32	15	10	15	10	6	3	4	103
WOMEN	14	29	11	12	9	5	3	1	2	86

is no gap of this kind, and the table would not be made any longer by adding any subjects who have been excluded from the random sample. In other words, it is again evident that the extremes of yellow-blue weakness are continuous with the normal grouping, while in red-green vision the colour blind form separate groups. It is also to be inferred that yellow-blue vision is much more variable than red-green vision when the red-green blind have been excluded.
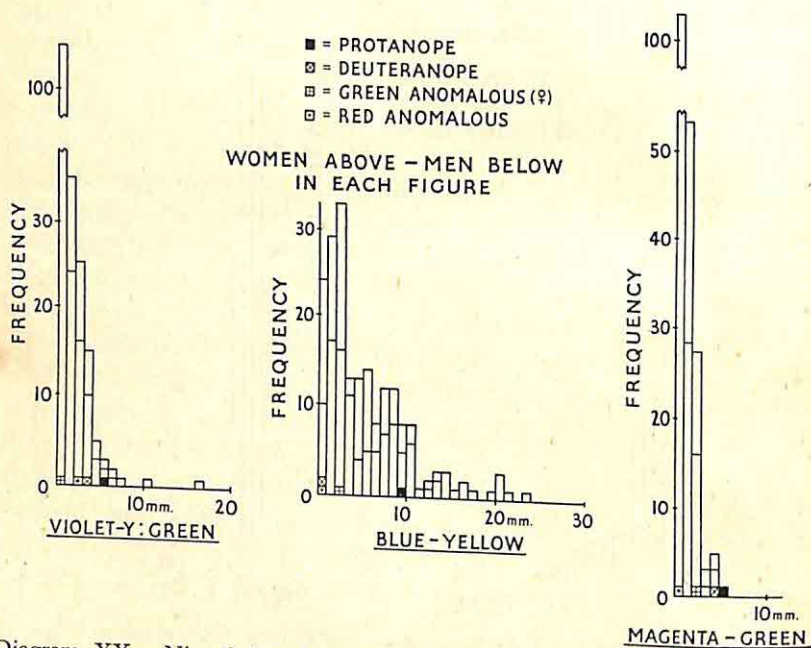
Diagram XX.   Nine Colour Experiment.   Matching Ranges: 106 Men;   87 Women (Magenta-Green 105 Men): Millimetre Steps

The Chi-squared test shows no difference between women and men in yellow-blue ranges, and since no subjects have been excluded on account of exceptional yellow-blue weaknesses, it may be inferred again that yellow-blue weaknesses are not sex-linked. All the extreme subjects showed difficulty with appropriate colours in daily life or in other tests.

Table 55 and Diagram XX show the ranges in the yellow-green and violet test for men and women. The difference between men and women shown in this table is almost significant statistically, having a probability between 1% and 2%. It therefore suggests that women are rather more sensitive than men in this test, but not very convincingly. The weakest subject is a man.

TABLE 55

YELLOW-GREEN+VIOLET RANGES : MEN AND WOMEN

Range in mm.	0·5	1·0	2·0	3·0	4·0	5·0	6·0	7·0	8·0	13·0	17·0	Totals
MEN	14	35	24	15	9	3	1	1	0	0	1	103
WOMEN	14	41	11	9	5	2	1	1	1	1	0	86

Of the subjects who had matching ranges of 6.0 mm. or more several should be mentioned individually. One woman who had weaknesses in all colours, including yellow-green and violet, had no difficulty with the Ishihara Test, but was unable to read the blue-green figures in Stilling's Tables. She knew of no colour-defective relatives. Violet was not at all darkened for her, but for another woman who showed similar defects it was very darkened. Another woman, who was normal in red and green, but who had blue and yellow weaknesses, was also weak in violet and it was darkened for her. She made five errors and was doubtful about six other figures in the Ishihara Test, was unable to read the blue-green figures in Stilling's tables, and had a slight divergent squint, affecting the left eye. She believed that she saw pink wallpaper a deeper hue with the right eye than with the left. She was tested with each eye separately, as well as with both together, and no differences in sensitivity were found between the eyes. Another woman subject, who had a range of 13.0 mm. in yellow-green and violet, was also very blue-yellow weak and slightly red-green weak. Violet was of normal brightness for her. She had a special interest in colours and their psychological meanings, and it is possible that an interest of this kind may sometimes be a compensation for colour weakness of which the subject is not aware.

No relationship was found between violet defects and darkening of the violet, and this is difficult to reconcile with the pigmentation theory of blue and violet weaknesses, and with the trichromatic theory of colour vision.

Table 56 and Diagram XX show the ranges for men and women separately in the purple-green test. The difference between men and women on this test is not statistically significant.

The study of matching ranges confirms that of deviations in showing that defects of sensitivity in the intermediate colours, orange, yellow-green, blue-green, violet and purple, are due to weaknesses in one or more of the primaries, red, yellow, green and blue. These

primaries must include yellow, for weaknesses in yellow are not determined by red-green weaknesses. There is a tendency for those with large red-green ranges to have ranges proportionally less large as the axis tested passes round towards yellow and blue and then

TABLE 56

PURPLE-GREEN RANGES : MEN AND WOMEN

Range in mm.

	0·5	1·0	2·0	3·0	4·0	5·0	*Totals*
MEN	22	34	28	15	1	2	102
WOMEN	15	31	25	12	2	2	86

larger again as it returns to red and green the other way. Similarly those with large yellow-blue ranges tend to have ranges less large in orange and blue-green or in yellow-green and violet and still less in red or purple and green. Those who have large ranges both in the red-green and in the yellow-blue tests are the ones who have marked weaknesses in all the other tests as well. Darkening of the violet end of the spectrum sometimes accompanies yellow-blue weaknesses, but not always, just as darkening of the red accompanies red-green weaknesses only in certain cases.

Like the deviations in these five tests, the matching ranges have an important general feature, which is shown in Table 57. The

TABLE 57

MODAL MATCHING RANGES : MEN AND WOMEN

Test :		R-G	O-BG	Y-B	YG-V	P-G
Range (mode) in mm.	MEN ..	0·5	1·0	2·0	1·0	1·0
	WOMEN ..	1·0	2·0	3·0	1·0	1·0

modal range increases as the axis of the test revolves clockwise from red and green to yellow and blue, and then it decreases again as the axis completes the revolution and returns to red and green from the other side. This confirms the impression from the study of individual ranges, that the red-green and yellow-blue axes are limiting positions, probably almost at right angles to each other. Yellow-blue vision is less sensitive than red-green vision (excluding the red-green blind and anomalous subjects), whether measured by ranges or by deviations.

The measurements of deviations suggest, rather inconclusively, that men tend to be more scattered in mid-positions than women, and the matching ranges show that women are more often colour weak than men in the red-green test. In order to test further the hypothesis that there might be sex differences, the colour thresholds, measured from the average matching positions to the points at which each colour appeared different from the standard, were calculated. The mean differences between men and women for these colour thresholds were tested by the standard error technique. No differences were found, even on the most lenient level of statistical probability. It appears therefore that the only clear sex difference is that women more often have large red-green ranges than men (excluding the red-green blind and anomalous).

DARKENED VIOLET

In the two groups, 103 men and 106 women (excluding all red-green blind and anomalous men or women, but including a number of women known to have colour-blind relatives), there were three men and three women for whom the spectrum violet filter was darkened by more than three times the standard deviation of brightness levels of violet for the remaining 203 subjects. Most of these have been mentioned already, but, because of the theoretical interest of the darkening of the violet end of the spectrum, which appears to have been discovered by Edridge-Green,[6] notes about them will be included again here. Knies mentioned a similar defect.

The three men with darkened violet were all yellow-blue defectives. The first was a blue-yellow weak subject who also had weakness in yellow-green and violet, without much deviation. For him the loss of violet sensitivity was attributable to his defect in blue, which was much greater, but the darkening of the violet extended into the blue. The second was a blue and violet deviant with moderate ranges in the blue-yellow and yellow-green+violet tests, and consequently he was not weak in yellow or yellow-green. He was a little weak in green, however, and called it " blue ". For him, again, the violet weakness would appear to be due to the blue defect, but the darkening of the violet also extended into the blue. The third was very similar, showing rather smaller, but marked blue, violet and green deviations, and a large yellow-blue matching range. One of the women was exceptionally yellow-blue weak, and this affected orange and blue-green as well as violet and yellow-green, and purple and green. She had a very slight red-green weakness. The second

was similar though her defects were less marked, and the third was similar again, but without the slight red-green weakness. All six subjects with darkened violet were therefore yellow-blue weak or blue deviants, and the blue part of the spectrum was slightly darkened though much less than the violet part. For the most extreme the blue part was markedly darkened.

It is interesting that the proportion of subjects with darkened violet rays should have been almost 3% for each sex. Approximate frequencies for a sex-linked character, based on the observed frequency of 3% of men showing it are indicated in Table 58. If

TABLE 58

APPROXIMATE EXPECTED FREQUENCIES OF DARKENED VIOLET IN WOMEN, ON BASIS OF 3% AMONG MEN, IF IT WERE A SEX-LINKED CHARACTER

MEN: Dark. Violet	Normal Violet	WOMEN: Darkened Violet		Normal Violet
		Homozygous	Heterozygous	Homozygous
x 3%	y 97%	x^2 0·1%	$2xy$ 5·8%	y^2 94·1%

it were a dominant all heterozygous women would show it, and there would be 0·1% +5·8% or 5·9% of women with the defect. If it were a recessive, then none of the heterozygous women would show it, and there would be only 0·1% of women with darkened violet. Since the frequencies are about 3% for men and women the figures certainly suggest no sex-linkage, but the differences between observed and expected frequencies are not statistically significant for a dominant, though they are decidedly significant on the assumption that it is a sex-linked recessive. These data, therefore, indicate that darkened violet is unlikely to be sex-linked, though it might possibly be a sex-linked dominant.

In the observed sample of 209 subjects, darkened violet is about as frequent as darkened red is among men (as found in protanopes) and the degree of the darkening is about as great. It is sometimes associated with yellow-blue weakness, but not always, just as darkened red is not always present in red-green blindness. The most extremely yellow-blue weak or blue deviants are not necessarily those with darkened violet, just as the most extremely red-green blind are not necessarily those with darkened red. Just as the darkening of red is not specially associated with red deviation rather than with red-green blindness, so the darkening of violet is not necessarily

associated with blue-deviation rather than with yellow-blue weakness. Thus, although, as Walls[7] has predicted, there are two classes of blue-defectives, those with and those without darkened violet, they are not, as he suggested, due to shifting of blue sensitivity towards green (darkened violet) and of green towards blue (violet not darkened) respectively. They are both yellow-blue defectives in one group of whom there is darkening of violet. Since darkened violet is not necessarily associated with blue defects, it cannot be explained purely by pigmentation of the optical system.

WOMEN WITH COLOUR-BLIND RELATIVES

Excluding three red-green blind women and one who was green anomalous, altogether 26 women with relatives who were major red-green defectives took part in this experiment. Some were found by chance, others were invited because of their known relation to a colour-blind person. Ten were sisters, four were mothers, seven daughters, two fathers' daughters' daughters, two fathers' sisters' daughters, and one was a mother's father's brother's daughter's daughter of a major red-green defective. Most of the red-green defective relatives were men, and some of the 26 women had several colour-blind relatives, so that all the relationships have not been exhaustively specified above.

If the mean matching point in the red-green test is calculated for the 26 women with colour-blind relatives, it is found to be not significantly different, even on the most lenient reckoning, from the mean for the remaining women subjects, and, although the group of women with red-green defective relatives includes some with fairly large deviations, the standard deviations of the mid-points of the two groups are not statistically different. Consequently it would appear that deviation in the red-green test is not a consistent indication of a woman being heterozygous for red-green blindness, but it may be an indication in some cases.

If the red-green matching ranges are classified as in Table 59, showing the numbers of women with and without colour-blind relatives, who had less than twice the modal range or two or more times this range, then Chi-squared may be calculated on the assumption that the women without colour-blind relatives represent the group homozygous for normal red-green vision, and the women with such relatives represent the group heterozygous for red-green blindness. Chi-squared is more than three times as great for this 2×2 table as would be required for statistical significance at the

1% level. Thus there is no doubt that the 26 women with red-green blind relatives tended to have much larger matching ranges than the 80 without known colour-blind relatives. This supports the conclusion of the rotating disks experiment, that a large matching range is a

TABLE 59

PROPORTION OF WOMEN WITH COLOUR-BLIND RELATIVES WHO HAVE TWO OR MORE TIMES THE MODAL RANGE IN RED AND GREEN

	Less than twice Modal R-G Range	*Two or more times Modal R-G Range*
No known R-G blind Relatives	60	20
Known R-G blind Relatives	5	21

strong, though not absolutely certain indication of the heterozygous condition for red-green blindness in a woman. The proportion of presumed and certain heterozygotes in this table is 26/106, or 24.5%, which is much higher than the expected proportion of 13.2% based on the assumption of 7% of red-green blind men. This is due to the inclusion of 17 who were specially invited, leaving 9/89, or 10% who were found by chance, which agrees with the expected 13.2%, from which it is not statistically different.

The presence of two X chromosomes in women must have a steadying effect on the red-green mid-points, which are more scattered in men, who have the XY chromosome condition. This suggests that the establishment of a balance between red and green sensations in individual development might be due to the influence of genes located on the X chromosomes. When there is only a single X chromosome approximately half of these genes will be missing—a condition normal in men—and in consequence the establishment of that balance will be more liable to disturbance than it is in women. Another possibility is raised, namely that in women the normal heterozygous condition, that is to say, the condition when the gene for red-green blindness is carried on one X chromosome and not on the other, and which may be represented X'X, leads to a greater variability of red-green thresholds and not to a disturbance of the balance of these sensations against each other. In other words, variability of normal red-green balance is associated with the XY chromosome condition in men, but variability of red-green thresholds

in women is associated with the X'X condition. Major red-green defect, which is due to the X'Y condition in men or with the X'X' condition in women, is an extreme exaggeration of the disturbances of thresholds when it appears as colour blindness, or an extreme disturbance of the red-green balance when it appears as anomalous colour vision. Further investigation of the implications of these speculations is most important, especially in connection with the two-locus and multiple allelomorph theories to be discussed in Chapter X.

Table 60 shows the peculiarity found in 15 women related to major red-green defectives whose defect had been accurately studied

TABLE 60

Nature of Peculiarity, if any, in Heterozygous Women with Various Types of Red-Green Defective Relatives

| | Peculiarity of the Heterozygous Women : | | | |
Relative	Green Deviation	Red Deviation	Twice Modal R-G Range	None
Protanope	—	—	3	—
Deuteranope	1	—	8	—
Red Anomalous	—	—	—	1
Green Anomalous	1	—	1	—

in the present experiment. It will be seen that twice the modal red-green range is on the whole distinctive of the female relatives of protanopes and deuteranopes, but whether a red or green deviation is equally characteristic of the female relatives of red and green anomalous men respectively cannot be determined from such small numbers. This matter will be dealt with again later.

THE ISHIHARA TEST

Excluding the anomalous and red-green blind subjects, who will be dealt with in the next chapter, 45 men and 51 women who took part in the present experiment also did the Ishihara Test, under carefully standardised conditions, using a daylight blue lamp, as described in a previous chapter. It is interesting to tabulate the numbers of errors made by these subjects and to compare them with the results of the red-green colorimeter test. Table 61 shows the numbers of subjects in the various classes in the colorimeter test and the corresponding numbers of errors on the Ishihara Test,

giving the range and the modal number of errors for each group, except where there were only two or three subjects.

TABLE 61

ERRORS ON THE ISHIHARA TEST

Colorimeter Test : Classification	Numbers of Errors on Ishihara Test			
	MEN		WOMEN	
	Number of Subjects	Number of Errors	Number of Subjects	Number of Errors
"Normal"	32	0—8 Mode=1	19	0—9 Mode=1
"Deviant"	6	1—8 Mode=3·5	11	2—11 Mode=2
"Extreme Deviant"	2	3 and 21	3	1, 3 and 3
"Red-Green Weak"	5	1—7 Mode=4	18	0—11 Mode = 5
Totals	45	0—8 and 21	51	0—11

It will be seen that the Ishihara Test gives a very slender indication of the degree of red-green defect among these subjects. The one extreme deviant man who made twenty-one errors would have been classed as "totally green blind" on the Ishihara Test alone, and it is a possibility that he should have been classed as green anomalous on the red-green colorimeter test. Apart from him, it appears that the modal number of errors tends to increase from 1 to 5 with increasing red-green defects, colour weakness having more influence than deviation in producing errors. Since the range of errors can be as great, or almost as great, with subjects who show no colour defects, as with extreme deviants and the red-green weak, the Ishihara Test could not be used to discriminate between these and normal subjects. The matter may be confirmed by calculating the mean number of errors made by the " normal " men and women as a group (4.25) and by all the other subjects taken together (5.14). The difference between these means divided by its own standard error is then $0.89/.502 =$ 0.177, which is not statistically significant. This confirms the result of the rotating disks experiment, and it confirms common experience, because nobody has been able to use the Ishihara Test successfully for this purpose, and it has never distinguished between deviants and colour-weak subjects—indeed, if we only had the Ishihara Test as a guide we should never have suspected such a difference.

In addition, a person may make up to about ten errors on the Ishihara
Test without there being any certainty that suspicions of red-green
defect are confirmed. These conclusions fully accord with expecta-
tions based on the principles on which the Ishihara Test and similar
tests are constructed. None of the colour differences between the
individual spots used in it are subliminal, and it is doubtful whether
a test in which subliminal differences were to be used could be pro-
duced by colour printing. Every expert in psycho-physical measure-
ments knows, however, as a first principle, that subliminal differences
must be available for an efficient test of sensory acuity. This short-
coming of the pseudo-isochromatic tables is met by arranging the
spots of colour in confusing patterns, so that some can read the figures,
others can see the differences between the dots and not read the
figures, and others again cannot even see the differences between the
dots. For subjects with normal, deviant or slightly weak colour
vision, the difference between two and eight or ten errors is due to
chance factors which are irrelevant to the sensory acuity being tested.
For the red-green blind and anomalous subjects, however, many or
all of the differences between the dots may be subliminal, with the
result that these subjects make more than about 80% of errors, and
may be picked out with some confidence. As explained in a previous
chapter, unless there were a marked gap between the weakest of the
deviant and colour-weak subjects and the best of the colour blind
and anomalous, a test constructed on these principles could not be
reliable at all. It is obvious that the true remedy for its defects is to
have the differences between the coloured spots under the tester's
control, and that is done in the colorimeter tests.

ART STUDENTS

Seventeen of the subjects who took part in this experiment were
art students, kindly brought from the Glasgow School of Art by
Miss Jean Gardner. Three of these were men and fourteen were
women. One of the women was green anomalous. One of the men
was an extreme green deviant who made twenty-one mistakes in the
Ishihara Test. Since the woman was far beyond the normal range of
deviations on the green side, her readings have been omitted from the
following calculations, but the man was less extreme and his readings
have been included. If the mean matching points for the sixteen re-
maining art students in all five tests are calculated, they are found to
differ only within the limits of chance expectation from those of the
other subjects, excluding the colour blind and anomalous. Hence art

students cannot be said to show any greater ability as far as matching points or deviations are concerned than the rest of the population. With the exception of the anomalous woman they are quite normal on the average in matching points for all the nine colours tested.

If all the matching ranges for all the colours tested are tabulated for art students, showing how many had less than twice the modal ranges and how many twice or more times the modal ranges, these numbers may be compared with the frequencies for the remaining subjects by the Chi-squared technique. This shows no significant differences. Certainly the art students seem to be a little more sensitive to red and green than the others, but the difference observed has a probability between 5% and 2%, whereas less than 2% would be required according to ordinary standards, in order that the difference should be considered convincing.

It can be concluded, in so far as this experiment shows, that art students are neither better nor worse at colour discrimination than other people, with the exception of the green anomalous girl, who had a rare and extreme defect for a woman, of which she was unaware, and which does not appear to have been a disadvantage in her work. The anomalous, however, are not less particular in colour discrimination than the normal; they discriminate in slightly different ways, and it is almost certain that red-green blindness would be a disadvantage for an art student. This is suggested by the fact that several of the red-green blind subjects had discovered their weaknesses in school art classes.

In connection with this problem it is interesting to note that Geddes[8] has concluded from a study of the colour vision of Fijian natives, carried out with the shortened form of the Ishihara Test, that " the achromatic nature of most Fijian decorative art is not the result of defective colour vision or lack of aesthetic discrimination of hue, but is dictated by an almost complete absence of suitable permanent dyes ". In the present research a converse conclusion may be drawn : that the interest of these art students in coloured artistic work was not the result of unusually sensitive colour vision or discrimination of hues, but was determined by other factors, probably of an emotional and personal nature.

RACE AND PIGMENTATION[4]

Vernon and Straker[3] have given evidence that there is a connection between the frequency of red-green defects and skin or hair pigmentation. More subjects were failed on a combined form of the Ishihara

Test and Stilling's Tables, used for testing recruits for H.M. Navy, in those parts of the British Isles (the South West and Western districts) in which more dark people are found, and fewer were failed in those parts (the North East and East) where more fair people are found. This confirmed evidence given by Burt (privately communicated but published later)[2] in which a correlation of $+.174$ was found between darkness of pigmentation of the iris and colour-vision defects detected by a group of tests not specified in detail. These publications are extremely interesting, and it is most unfortunate that when the present experiment was undertaken I understood from personal communications that skin pigmentation was the central interest rather than pigmentation of the iris. Hence the subjects of this experiment were classified on hair and skin pigmentation. Burt shows that hair colour is not related to colour-vision defects, and in the end his main claim is a correlation of about $+.218$ between the yellow-blue colour sensitivity component (when the results are factorised by a method which he explains) and pigmentation of the iris. Vernon and Straker's results suggest that red-green defects might be connected with racial differences if not with differences of pigmentation, because the South West and Western parts of the British Isles are inhabited by people more closely related to the early settlers, who were driven to the West by the Scandinavian and Northern tribes who followed. All, however, are of Indo-Germanic origin. Geddes[8] has given evidence that there is a low incidence of colour blindness among Fijians, and this is also true of American Indians and American Negroes, who are all of Negroid racial origin. All these discussions, however, refer to red-green blindness and not to small variations of colour sensitivity. The relation between pigmentation and red-green blindness will be dealt with in the next chapter.

The subjects of the nine-colour experiment were classified " dark " or " fair ", mainly on the basis of skin pigmentation. In order to compare these groups the mean points of change from " redder " to " equal " and from " greener " to " equal " in the red-green test and the corresponding points of change for the four other tests were calculated for each group, together with their standard errors. No statistically significant differences were found in any colour sensitivity, between " dark " and " fair " subjects, taking men and women either separately or together, nor were any significant differences found between men and women, taking " dark " and " fair " either together or separately. The groups compared included all the subjects who did the experiment, with the exception of red and green anomalous and red-green blind subjects.

This part of the experiment does not give any support to the theory that colour-vision sensitivity of non-colour-blind subjects might be related to skin and hair pigmentation. If results such as reported by Burt and by Vernon and Straker were possibly due to racial differences rather than to differences of pigmentation taken by itself, then an investigation in a single centre, such as Glasgow, might give the result just reported. Then comparisons between parallel investigations in different centres, such as Aberdeen and Plymouth might show the kind of differences reported by Vernon and Straker, irrespectively of skin pigmentation. This possibility is supported by the results given by Geddes for Fijians and others of Negroid stock, and by the comparisons given in the next paragraph between Indians, Europeans and West Africans.

It was possible to include twenty subjects of dark or moderately dark skinned race, by the courtesy of Mr. A. Aaron, Warden of the Glasgow University Student International Club. In order to test the hypothesis that skin pigmentation or racial difference might have a bearing on colour sensitivity they were classified as shown in Table 62, and their sensitivities in all the five tests were calculated.

TABLE 62

NON-EUROPEAN SUBJECTS IN THE NINE-COLOUR TESTS

	Indian	West African	Turkish	Jewish
MEN	7	5	1	1
WOMEN	3	1	0	2

Their deviations were taken separately from their matching ranges in the hope of making the test more exacting, and the comparison between them as a group and the remainder of non-colour-blind subjects who did the experiment is shown in Table 63.

None of the differences of mean mid-points between the European and non-European groups is significantly different from zero, but the modal range for the non-European group in the yellow-blue test is more than twice as great as that for the European group. The effect of this is apparent in related tests, because the rate of increase of the modal range as we pass clock-wise round the colour circle starting with the red-green test is greater for the non-European than for the European group, until we reach the yellow-blue test, and then the corresponding rate of decrease is equally great as we return to the red-green axis, on which the modal ranges for the two groups are the same. This suggests the conclusion that there is a tendency for yellow-blue vision to be weaker in non-Europeans than in Europeans,

while red-green vision is the same for both. This is borne out by tabulating the numbers of subjects in the European and non-European groups who have less than twice the modal range and two or more times the modal range of the Europeans in each test separately. The Chi-squared test then shows that the differences

TABLE 63

MODAL RANGES AND MID-POINTS IN MILLIMETRES FOR THE FIVE TESTS; EUROPEAN AND NON-EUROPEAN SUBJECTS COMPARED

	RED-GREEN		ORANGE+ BLUE-GREEN		YELLOW-BLUE		YELLOW-GREEN+ VIOLET		GREEN-PURPLE	
	Mid-Point	Modal Range	Mid-Point	Modal Range	Mid-Point	Modal Range	Mid-Point	Modal Range	Mid-Point	Modal Range
Whites (European)	21·38	0·5	13·27	1·0	21·40	1·5	14·93	0·5	19·45	0·5
Non-Europeans	21·85	0·5	13·33	1·5	22·48	3·5	14·98	1·0	19·63	1·0

are not significant for the red-green or purple-green tests, but for the other three tests they are well above the 1% significance level, being most extreme for yellow-blue. It is interesting that in the red-green axis there should be no difference between the groups, while the difference is greatest in the yellow-blue axis and of a more moderate degree in the intermediate axes. This gives indirect support to the view that the red-green and yellow-blue axes represent two difference modes of colour vision, which are independently variable from race to race. There is, however, no tendency for the non-European group to make more deviant colour matches in any of the tests than the European group.

Since the difference of sensitivity lies in the yellow-blue axis, we might infer that it was due either to an hereditary weakness in yellow-blue sensitivity (but not in red and green) affecting certain racial stocks, in this group mainly Indian and Negroid, or to the effect of pigmentation filtering out certain light rays as they pass through the optical system, or to other causes, such as lack of skill in distinguishing colours or different naming habits. At present we are not in a position to decide definitely between these possibilities. The tests used are, however, independent of naming, and, as shown in a previous section, art students, who have special practice in distinguishing and matching hues, are no better at the tests than the

rest of the population, excluding the colour blind. These two possibilities may be ruled out, therefore, at least provisionally.

The theory that the difference is due to pigmentation of the optical system acting as a colour filter would seem improbable, though it might be a part explanation. The yellow pigmentation absorbs fairly heavily in the violet and blue parts of the spectrum and to some extent as far as green. Blue weaknesses owing purely to this cause would therefore always be strongly associated with darkened violet, but this expectation is not fulfilled, though there is a small tendency for darkening of blue when it is deficient. Yellow weaknesses would be explained by relative lack of yellow pigment, which intensified blue against yellow. The dark peoples tested, however, as often show yellow as blue weaknesses, and not only blue and yellow deviations but also blue-yellow matching ranges of exceptional magnitude must be accounted for, and, if the yellow pigment absorbs blue-green and green, then green weakness should be highly correlated with blue-defects, another expectation which is not satisfactorily fulfilled. The common confusion of blue and green is not due to green but purely to blue weaknesses.

We are left with the theory that yellow-blue minor defects are hereditary peculiarities of certain racial stocks, resulting from diminution of sensitivity to certain light rays, explained only to a small extent by yellow pigmentation of the optical system. In the group of non-Europeans there were six West Africans, and nine Indians who were of Dravidian stock. If the numbers in these two groups who have less than twice the European modal range and two or more times that range, in the three tests in which the non-Europeans showed a significant difference from the European group, are tabulated and pooled for the three tests, the influence of the yellow-blue weaknesses in the Negro and Dravidian groups may be compared. The Chi-squared technique shows that Negroes are significantly more often yellow-blue weak than Dravidians. This confirms the theory that yellow-blue weakness is a racial peculiarity, and suggests that it is specially characteristic of people of Negro racial stock, so far as this experiment can show. The six West Africans, however, were decidedly the blackest subjects tested, and the possibility that pigmentation is partly the cause of their yellow-blue weakness must not be overlooked, improbable though it seems. It would be extremely interesting if groups of at least 100 subjects each of Mongolian, Indo-European, Negro and Australasian stock could be tested and compared.

FACTORIAL ANALYSIS,[9,10]*

The table of intercorrelations between the measurements of
" colour weakness " for the subjects who fell into the random sample,
men and women together, excluding the red-green blind and anoma-
lous subjects, was factorised by the simple summation method.
Three factors were extracted and the loadings for these are shown
in Table 64.

TABLE 64

FACTOR LOADINGS FOR THE TEN COLOURS TESTED : GREEN (P) BEING THE
SPECTRUM GREEN TESTED IN COMBINATION WITH PURPLE;
BRIGHTNESS LOADINGS SUBSEQUENTLY GRAFTED

TEST	FACTOR		
	I	II	III
Purple	·335	+ ·424	− ·519
Red	·136	+ ·663	− ·281
Orange	·136	+ ·613	+ ·378
Yellow	·443	− ·200	+ ·189
Y-Green	·143	+ ·515	+ ·430
Green (P)	·359	− ·342	+ ·490
Green	·363	− ·554	+ ·353
B-Green	·406	− ·524	− ·320
Blue	·617	− ·073	− ·334
Violet	·288	− ·522	− ·386
Brightness	·171	− ·074	− ·244

It is worth mentioning that the table of intercorrelations con-
tained many negatives, and had a bipolar hierarchy before the first or
general factor was extracted. The factor loadings in Table 64 show
that the general factor is much smaller than usually found in factorial
analysis, and this corresponds to the presence of many negative cor-
relations and to the greater weight of the second and third factors.
The negative loadings, as in previous correlation tables, resulted
from the frequent tendency of deviations to outweigh matching
ranges, especially in the red-green test. This tendency expresses the
way in which certain colours are balanced against each other: red
against green and yellow against blue. Red is in general much more
finely balanced against green for normal subjects than yellow is
against blue, and in consequence red-green tests are much easier to
do than yellow-blue tests. This is clearly represented in the factorial

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* The writer is greatly indebted to Professor Sir Cyril Burt for his help with
this part of the work.

analysis, because the red-green factor is the first bipolar and the yellow-blue the second: their relative weight in colour vision is indicated by their order in the analysis.

It is perhaps necessary to say that the measurements inter-correlated were all taken, as in previous experiments, from the mean matching point to the point at which the subject just distinguished (or just failed to distinguish) the colour tested from the standard. The brightness measurements, as before, were readings of the shutter on the standard side of the colorimeter, taken when the variable was matched in brightness with the standard at the point of average colour matching for the whole group. This was therefore a colour match as well for the majority and made brightness matching more reliable. In some of the tests the right shutter was used to control brightness. For these its readings were converted algebraically into virtual readings for the left shutter. In each case two colours were involved in each brightness measurement, as explained in a previous chapter, and therefore the effect of the unwanted colour was partialled out of each brightness correlation.

The factorial analysis suggests the following interpretation. Factor I expresses general ability to discriminate the test spots under the conditions of the experiment, special disabilities in colour sensitivity being excluded. This ability is most highly correlated with blue sensitivity, and therefore it may be inferred that, special disabilities apart, a test of blue would be the best general test of this sensitivity. Red and orange give the smallest loadings in this factor, and are consequently the least efficient measures of this ability. Greens and yellows are intermediate. Blue-green is higher than violet. Brightness has a low positive correlation with this factor, which is, nevertheless, a measure of colour-free sensitivity.

Factor II expresses the way in which colour vision is affected by variations in the balance between red and green sensitivities. Red has the highest positive loading; green the highest negative. It is striking that orange is very nearly as high as red and blue-green almost as high as green. Violet, rather unexpectedly, has a high negative saturation and blue a low negative. It is not easy to inter-pret violet, because this was by far the least monochromatic of the colours used (except purple), and this might explain the curious displacement of yellow-green. It would have been easier to under-stand that yellow-green should have a small negative loading, between green and yellow, and violet a small positive loading, placing it with the " red " rather than with the " green " group. Brightness has a negligible correlation with this factor.

Factor III shows the effect of variations in the balance between yellow and blue sensitivities. The loadings on this factor are rather irregular, and yellow has an unexpectedly small loading, while that for blue is not so high as for violet and purple. While the factor might suggest a yellow-green and violet contrast, rather than yellow and blue, the probable error for 192 subjects is rather high for any confidence to be placed on small differences between factor loadings in a third factor, and these loadings will be unduly affected by errors. In general the third factor suggests the contrast of yellows against blues. Brightness is correlated with the blue side of this factor, which confirms the frequently made observation that changes towards blue tend to be confused with darkening and changes towards yellow with brightening of the variable in the yellow-blue tests. Brightness, however, is not closely related to any measures of colour sensitivity.

It is striking that this factorial analysis confirms the expectations based on a four-colour type of theory in which there are balanced opposites, and it puts into a generalised mathematical form the peculiarities of individual subjects. In discussing these results it is important to bear in mind that no colour blind or anomalous subjects were included. The factorial analysis shown in Table 64 expresses the variation in sensitivity of normal, colour weak and deviant subjects. If the usual proportion, about 7% of red-green blind subjects were included in the correlation table, their readings would be so extreme in comparison with those of the remainder, that the negative correlations for red and green would be converted into positive correlations of equal magnitude. It is obvious, therefore, that correlations obtained from combining such disparate groups would be meaningless figures, and the groups must be separated. The factorial analysis for the colour blind and anomalous subjects will be discussed in the next chapter.

Among normal, colour weak and deviant subjects, therefore, we may say that the most common special disability is a disturbance of the red-green balance, giving red or green deviation, scarcely affecting brightness at all, and in which one colour is diminished to the advantage of the other. A less prominent form of special disability is the disturbance of balance between yellow and blue, in which, again, one is diminished to the advantage of the other, but here there is a tendency for loss of blue sensitivity to correspond to loss of brightness but no such tendency for yellow. The general factor expresses variation in sensitivity in so far as it is not affected by loss of saturation or hue, while the first bipolar factor expresses

losses in red (or green) which are balanced by gains in green (or red), and the second bipolar expresses losses in yellow (or blue) which are balanced by gains in blue (or yellow). This factorial analysis, therefore, precisely summarises, in a generalised form, what could have been predicted from a study of the individuals who did the experiment, and it does not tell us anything new about colour vision, except that it gives an exact quantitative expression to the average tendencies revealed. The value of factorial analysis is therefore the same here as the value of statistical analysis in any other psychological study : it clarifies what we know, formulates it precisely in quantitative terms and enables us to distinguish clearly between the tendencies operating in the data we examine. It enables us to interpret data with some confidence, when mere inspection might have led to confusion.

The first two factors might with difficulty have been made to support a three-colour theory. The first could be said to express blue sensitivities, the second red and green. If the third factor is taken into account, however, a three-colour theory becomes extremely difficult and it cannot be neglected.

Burt[2] has published a similar table derived from intercorrelations of measurements of sensitivity to nine colours. His results were published after the MS. of this chapter was written. Altogether he had 227 subjects, and the experiments were carried out with rotating disks and other methods which he does not fully describe, but which would involve the use of polychromatic colours. It is not stated what technique was used for desaturating the colours tested, and the psycho-physical methods which were used are not specified. No precautions were taken to separate the red-green blind and

TABLE 65

BURT'S FACTOR SATURATIONS FOR A TEST OF NINE COLOURS ON 227 SUBJECTS

Colour	Factor I	Factor II	Factor III
Crimson	·331	+ ·175	+ ·351
Red	·473	+ ·613	− ·264
Orange	·501	+ ·274	− ·313
Yellow	·769	+ ·229	− ·145
Y-Green	·478	− ·299	− ·230
Green	·520	− ·492	− ·288
B-Green	·259	− ·473	+ ·017
Blue	·384	− ·157	+ ·501
Violet	·363	+ ·130	+ ·371

anomalous subjects from the rest of the population. The simple
summation method of factorial analysis gave the factor saturations
shown in Table 65. Burt points out that this table of saturations
confirms expectations based on a four-colour theory of the Hering
type. However, a modification of these figures by rotation to elimin-
ate negative saturations as far as possible, gave the result shown in
Table 66. This table would support a three-colour theory of the
Young-Helmholtz type more strongly than a four-colour theory
of the Hering type. It is striking that the same results can be analysed
to support either kind of theory.

TABLE 66

BURT'S FACTOR SATURATIONS FOR A NINE-COLOUR TEST ON 227 SUBJECTS,
GROUP FACTOR METHOD WITH ROTATION

Colour	Factor I	Factor II	Factor III	Factor IV
Crimson	·149	·245	—·103	·427
Red	·121	·821	—·134	—·094
Orange	·221	·580	·161	—·151
Yellow	·342	·689	·265	·176
Y-Green	·025	·248	·574	·078
Green	·082	·127	·751	·053
B-Green	·172	—·149	·474	·137
Blue	·389	—·040	·091	·520
Violet	·194	·158	—·061	·455

An alternative interpretation of Burt's group factor analysis,
however, would appear still to support a four-colour theory, if
we carefully consider the analysis in terms of what is known of
colour vision. The first, or general factor, in his group factor analysis
is a yellow and blue factor, but not bipolar. It represents the varia-
tions of yellow and blue sensitivity in so far as these variations
are inseparable. The second is a red factor; the third green and
the fourth blue. The fourth factor shows the variations of blue in so
far as they are not inseparable from those of yellow. Burt himself
treats the first factor in the way mentioned above in part of his dis-
cussion.

This interpretation would accord well with what is shown of
variations of colour vision elsewhere in this book, namely, that in
the four-colour scheme yellow and blue have a considerable tendency
to vary together while red and green are very strongly inclined to
vary inversely—in subjects who are not colour blind. In other words

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yellow-blue vision is much more prone to increase of matching range and less liable to deviations than is red-green vision. Thus Burt's group factor analysis actually accords very closely with the real state of affairs in a four-colour process.

Whatever may be said about the group factor analysis, it is a strong confirmation of the general results of the nine-colour experiment with monochromatic filters and purple, reported in this chapter, that Burt should have obtained a table of simple summation factor saturations essentially the same, but resulting from the use of completely different tests. It is interesting to note that in his table of intercorrelations for nine colours there are only three negatives, whereas in the table of intercorrelations for the ten colours (green appearing twice) used in the experiment reported in this chapter, there are fifteen negatives. This difference would correspond to the differences in technique. If Burt's measurements were made by desaturating colours with grey, which seems probable, the influence of deviations (so characteristic of the Rayleigh Equation) would not be prominent in his results. His experiment therefore helps to meet a criticism of the experiment reported in this chapter, namely, that the weight of the bipolar factors might have been due to the technique of experimenting. Since in his analysis the weight of the bipolar factors is also much greater relatively to that of the general factor than is usual in factorial analysis, this unexpected distribution of loadings between the factors in the nine-colour experiment cannot be explained as due to the technique employed.

Chapter 7

The " Nine-Colour " Experiment : Colour-Blind and Anomalous Subjects

In this chapter an account will be given of the defects of colour vision in the colour blind and anomalous subjects who did the nine-colour experiment. Of the 20 red-green blind men in this series, 2 were found by chance and 18 were invited because they were known to be defectives. Of the 9 green anomalous men all were invited. Of the 3 red anomalous men 1 was found by chance and 2 were invited. Of the 3 red-green blind women all were invited, and of the 2 green anomalous women 1 was invited and 1 found by chance. Twenty-six women who were known to have red-green blind relatives did the experiment.

The four classes : (1) Protanope, (2) Deuteranope, (3) Green anomalous and (4) Red anomalous, are again found to be clear and natural groupings which neither run into each other nor into the other groups of normal, deviant and colour-weak subjects. There are four separate curves corresponding to these four main types of red-green defectives. The general nature of colour blindness, as described in a previous chapter, was fully confirmed in this experiment and will not be repeated in detail here. Certain deuteranopes fail or almost fail to accept the normal mid-matching point on the green side. These will be called deviant or anomalous deuteranopes. A proportion of the red anomalous subjects do not have the red end of the spectrum darkened. Both of these types of defectives will be discussed more fully in later chapters.

Red-Green Defectives as a Group

Diagram XXI shows the matching ranges of the 23 red-green blind, 11 green anomalous and 3 red anomalous subjects who did the nine-colour experiment. It will be seen that the colour-blind subjects form one large group together, the green anomalous form a smaller group in the upper right-hand part of the diagram, and the red anomalous a much smaller group to the left. There is no distinction between protanopes and deuteranopes so far as range and deviation

are concerned. Those with darkened red tend to have red deviations to a small extent, but those with red of normal brightness do not consistently have green deviations.

The diagram shows that the red-green blind are very variable in range and deviation, and that there are no clear intermediates between the moderately colour blind and the anomalous. It shows the coherent nature of the two groups of anomalous subjects, and the wide gap between them. If we added the appropriate number of normal subjects (together with the deviants and colour weak), they would form a very large group of about 300, with ranges mostly
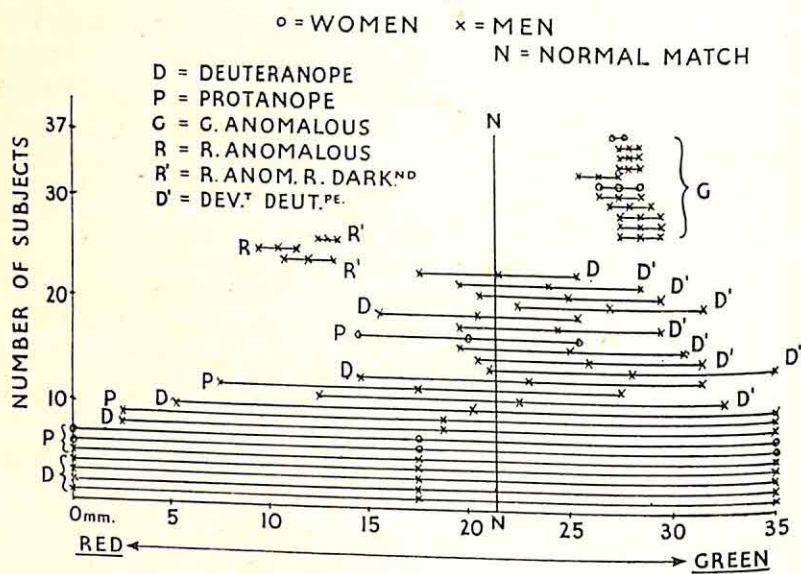
Diagram XXI. Nine-Colour Experiment : 37 Major Defectives in the R-G Test

smaller than those of the anomalous, but with much smaller deviations, and concentrated into a narrow column running up the normal centre line marked " NN ". It will be noticed that the red anomalous man for whom red was not darkened had a greater red deviation than the two others for whom it was darkened. Finally, it will be noticed that the colour matches of the red-green blind are, with one exception, always sufficiently great to include the average matching point of normal subjects, while the ranges of the anomalous are so small as to exclude the normal matching point by a wide margin. Red-green blind subjects who do not include the normal matching point are exceptions. They are among the deviant deuteranopes.

The darkening of the red transmitted by the Ilford Spectrum

Red Colour Filter, for the seven protanopes who did this experiment, can be compared with the normal brightness of the same red in the deuteranopes, in terms of the left-hand shutter readings for a brightness match of the two spots of light when the right slide was at zero (that is to say, pure red). The average left-hand shutter reading for the seven protanopes under these conditions was 8·6 mm., ranging from 6·0 mm. to 10·0 mm. The average for the sixteen deuteranopes was 24·7 mm., ranging from 18·0 mm. to 33·0 mm. Hence this experiment presents no difficulty in distinguishing protanopes and deuteranopes, and these two groups do not tend to run into each other.

" Dark " and " Fair "

The group of 37 red-green blind and anomalous subjects was sub-divided into "dark" and "fair" in the same way as described in the previous chapter for the normal, colour weak and deviant subjects. Table 67 shows the frequencies of " dark " and " fair "

TABLE 67

PROPORTIONS OF "DARK" AND "FAIR" AMONG RED-GREEN DEFECTIVES AND NORMAL SUBJECTS

	"Dark"	"Fair"
Normal, Deviant, Colour Weak	58	112
Red-Green Defectives ..	12	25

among the red-green defectives. compared with the frequencies among 170 non-defective individuals who did the same experiment, excluding any from the non-defective group who had been invited for special reasons. If this group of 170 is taken as fairly representing the whole population from which the defective subjects were drawn, then the proportions of " dark " and " fair " among the red-green defectives do not differ significantly from their proportions among the whole population. There is no tendency for red-green defectives to be more often " dark " or " fair " than any other subjects. When the great magnitude of their defects in colour vision is considered in comparison with the colour vision of ordinary subjects, it is clear that any tendency for pigmentation to be associated with red-green weaknesses should be brought out very emphatically by a comparison such as this, but no such tendency was found.

The Ishihara Test

Twenty-two of the major red-green defectives who did the nine-colour experiment also did the Ishihara Test, and the results of this are shown in Table 68. It will be seen that the number of errors made on the Ishihara Test does not distinguish either between extreme and moderate protanopes, extreme and moderate deuteranopes, or between any of these defectives and the red or green anomalous. All made twenty errors or more. In other words, where clear distinctions can be made with the anomaloscope, no clear distinctions can be made with the Ishihara Test.

TABLE 68

ISHIHARA TEST RESULTS OF MAJOR RED-GREEN DEFECTIVES IN THE NINE-COLOUR EXPERIMENT

		Number	Errors on Ishihara	Darkening of Red: Decisive	Indecisive
Protanopes :	Moderate	2	20, 24	2	0
	Extreme	2	24	2	0
Deuteranopes :	Moderate	6	20—24	4	2
	Extreme	3	24	3	0
Green Anomalous :		6	21—24	2	4
Red Anom :	Red Normal	1	24	0	1
	Red Dark	2	22, 24	1	1

Similarly, the distinctions between protanopes and deuteranopes, between red and green anomalous, and between red anomalous with and without darkened red, are also often indecisive on the Ishihara Test. Taking all twenty-two subjects, in six of them the red was darkened, but the Ishihara Test was indecisive for one of these and for 7/16 of those in whom the red was not darkened. It was considered "decisive" when three of the four plates supposed to distinguish protanopes from deuteranopes indicated correctly whether the subject's red was darkened or normal.

Factorial Analysis[1]

The three groups of red-green defectives provided three tables of intercorrelations between colour sensitivities measured from the ends of the colorimeter scale to the points of just noticeable difference from the standard yellow or grey. Protanopes and deuteranopes were not separated. These tables were analysed by

the simple summation method of Burt. A general factor was extracted first, followed by two bipolar factors. The factorial analysis of such tables is open to criticism, because the number of red-green blind subjects was only 23, of green anomalous only 9 and of red anomalous no more than 3. However, the difficulty of getting larger numbers of defective subjects to do these experiments is so great that it seemed to justify as complete an analysis as possible of such results as were available. In fact, no more red anomalous subjects were found for two years of regular testing in which more than 400 men and women were examined. In addition, the three groups, though small, were relatively coherent and distinct from each other and from the normal group, and the results of the analysis might be taken provisionally as representative, though not statistically significant in the usual sense. Under these conditions it is the general pattern revealed by the factorial analysis which is of interest, while small quantitative differences between the loadings are not important. Therefore the results must be viewed as applying strictly to the small groups actually tested, and as suggesting in general what might be expected from larger groups of a similar kind, and when viewed in this way they do throw light upon the problems of normal and abnormal colour vision. The factors given are all approximate.

The factorial analysis of the intercorrelations for normal, deviant and colour-weak subjects gave a general factor in which blue was most heavily loaded, followed by a bipolar factor in which purple, red, orange and yellow-green were set off against yellow, green, blue-green, blue and violet.

For the red-green blind subjects there was a general factor in which all colour sensitivities were very evenly loaded. This is shown in Table 69. The first bipolar, however, was now a yellow-blue factor, contrasting red, purple, violet, blue and blue-green against orange, yellow, yellow-green and green. Blue-green had the heaviest positive and yellow the heaviest negative loading. The second bipolar, however, was a red-green factor, in which red and green were combined so that they were contrasted as co-variants with yellow-blue sensitivity. For the red-green blind subjects red and green sensitivities are greatly diminished in contrast to each other in comparison with their relationship in normal colour vision, and it is striking that the factorial analysis reduced their combined effect to one polarity without including yellow, which goes into the opposite polarity with blue. On either the Young-Helmholtz or the Ladd-Franklin theory no such result would be expected, but red and green would be expected to combine with yellow and be set off

against blue in the colour blind. This factorial analysis therefore strongly supports the view that red-green blind subjects are not "dichromatic" except in appearance when very defective. They are still in reality "tetra-chromatic", but in some way have lost the contrast of red and green. This could be explained by Houstoun's theory, on which the red-green responses still remain in the colour blind, but

TABLE 69

FACTOR LOADINGS FOR 23 RED-GREEN BLIND SUBJECTS IN THE NINE-COLOUR EXPERIMENT; BRIGHTNESS LOADINGS GRAFTED

Colour Tested	Factor Loadings		
	I	II	III
Purple	·522	+·123	−·276
Red	·555	+·106	−·708
Orange	·546	−·002	−·461
Yellow	·424	−·570	+·294
Y-Green	·539	−·042	+·544
Green-P	·503	−·407	+·030
Green	·254	−·253	−·582
B-Green	·541	+·639	+·104
Blue	·361	+·371	+·691
Violet	·338	+·383	+·313
Brightness	·424	+·635	−·026

have ceased to be in contrast owing to the tendency of both red and green rays to excite both types of response together, while yellow also remains an independent response. This interpretation is confirmed by the second factor in the analysis, which sets off yellows against blues. It is essentially the same yellow-blue factor which was found in normal subjects, in whom it appeared third, and this change in order of appearance of the factors accords fully with general knowledge that red-green blind subjects are not abnormal in yellows and blues, which form the predominant colour contrasts for them. For normal subjects the predominant colour contrasts are between reds and greens. For the red-green blind subjects brightness is chiefly correlated with the general factor and with the blue side of the yellow-blue factor.

The analysis of intercorrelations for green anomalous subjects is shown in Table 70. It gave a general factor first, followed by a bipolar factor which contrasted blues and yellows, because orange, yellow, yellow-green and green have positive loadings while blue, blue-green, violet, purple and red are negative. It is important that

the blue-yellow factor was second and not third for these subjects. This stresses its increased significance for their vision in comparison with the predominant importance of the red-green factor among the normal. The third factor for the green anomalous contrasted orange, red, purple, violet and blue against blue-green, green, yellow-green and yellow. This can be called a red-green factor, although the loadings are somewhat irregularly distributed, which is not surprising with so small a number as nine subjects. It may be a form of the red-green factor of the normals distorted by chance

TABLE 70

FACTOR LOADINGS FOR NINE GREEN ANOMALOUS SUBJECTS IN THE NINE-COLOUR EXPERIMENT; BRIGHTNESS LOADINGS GRAFTED

Colour Tested	Factor Loadings		
	I	II	III
Purple	·395	−·162	+·332
Red	·257	−·190	+·158
Orange	·352	+·423	+·548
Yellow	·590	+·546	−·179
Y-Green	·167	+·539	−·332
Green-P	·544	+·533	−·164
Green	·590	+·105	−·540
B-Green	·120	−·699	−·570
Blue	·043	−·682	+·170
Violet	·525	−·413	+·567
Brightness	·774	+·093	−·535

errors. The important point, however, is that the first bipolar is a yellow-blue factor for the green anomalous as well as for the red-green blind.

Table 71 shows the factorial analysis for red anomalous subjects. The usual technique was followed, without reversals for the first or general factor, and in this red has a negative loading, and unless it is interpreted as a result of chance errors, this must be viewed as a specific disability for red. Since only about 7% or 8% of red-green major defectives are red anomalous there is little hope of a difficulty of this kind being settled without special steps being taken to collect about fifty red-anomalous subjects. At the rate of progress of the writer's research at the time of writing this would take about forty years or more. Since there were only three red-anomalous subjects, and one of them was peculiar in having a tendency to confuse purple

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with green, the irregularity of the loadings probably reflects his peculiarity and must be viewed as unimportant for the purpose of general inferences. The second factor contrasted orange, yellow, yellow-green and green with blue-green, blue, violet, purple and red, and is a blue-yellow factor. The third factor contrasted violet, purple, red, orange and yellow with yellow-green, green, blue-green and blue, and must be viewed as a red-green factor. Thus both the

TABLE 71

FACTOR LOADINGS FOR THREE RED ANOMALOUS SUBJECTS IN THE NINE-COLOUR EXPERIMENT; BRIGHTNESS LOADINGS GRAFTED

Colour Tested	Factor Loadings		
	I	II	III
Purple	+·003	−·279	−·238
Red	−·473	−·287	−·569
Orange	+·323	−·181	−·499
Yellow	+·517	+·655	−·349
Y-Green	+·024	+·328	+·505
Green-P	−·001	+·324	+·511
Green	+·795	+·514	+·441
B-Green	+·016	−·557	+·387
Blue	+·443	−·478	+·035
Violet	−·002	−·401	−·219
Brightness	+·228	−·333	−·219

green and red anomalous, as well as the red-green blind subjects, have a predominant yellow-blue factor, after the general factor has been extracted, while the red-green factor predominated for the normal subjects. In the green anomalous the green side of the red-green factor includes all colours from blue to yellow, whereas in the red-anomalous it includes all from blue to yellow-green, and for normal subjects it includes colours from violet to yellow. In the red-anomalous subjects brightness is positively correlated with the general factor, and with the red side of the red-green factor and with the blue side of the blue-yellow factor (as a negative).

The essential contrasts between these different types of subjects may be expressed by saying that red-green blind subjects differ widely from normals in the second bipolar factor, which for them contrasts red-green vision against blue-yellow vision, instead of being a first bipolar and contrasting red with green. In consequence they also differ in the predominance of yellow-blue vision, which

comes out in the first instead of the second bipolar. Both types of anomalous subjects also give this yellow-blue factor second instead of third, and so it dominates red-green vision in all red-green defectives. The red anomalous are peculiar in showing red as a special disability in the general factor. The peculiarities of the red-green blind are therefore the combination of red and green in the same polarity as co-variants against yellow and blue, and the predominance of the yellow-blue factor; the peculiarity of the green anomalous lies in the predominance of the yellow-blue over the red-green factor; the peculiarities of the red anomalous lie in the special disability in red in the general factor and in the predominance of the yellow-blue factor over the factor for red and green.

These interpretations confirm the view that certain red anomalous subjects are not quite symmetrically opposite to the green anomalous in the nature of their defects. While both have strengthened yellow-blue and weakened red-green vision, like the red-green blind, certain red anomalous have a special deficiency in red, although the green anomalous never have a corresponding special deficiency in green. The special peculiarity of the red-green blind is the functioning of red and green as co-variants, which is, of course, simply a mathematical way of saying that they are colour blind.

Factorial analysis of the intercorrelations for red-green blind subjects confirms the Hering-Houstoun theory against other colour-vision theories. That of the anomalous subjects is not explicable on the Young-Helmholtz theory or on Ladd-Franklin's theory, but could be explained on the Houstoun theory in the following way: For both red and green anomalous the whole system of red-green vision is dominated by the greater importance of yellow-blue vision. In certain red anomalous there is a special deficiency in red (although in one out of the three subjects red was not darkened), and the red-green axis really lies in the direction of red and green, whereas for the green anomalous it lies more in the direction of yellow-green and purple. It may be the directions of these axes which determine whether a subject is red or green anomalous rather than special defect in any given colour, but if the specific defect in red found in some red anomalous were confirmed by subsequent experiments, then this would appear to be an important characteristic. In so far as both types of anomalous subjects show a clear bipolarity of red-green vision, they are sensitive to differences between red and green, just like normal subjects, but in different ways. In so far as they both show predominance of yellow-blue over red-green vision, both may be described as red-green defectives, though their kind

of red-green defect is different from that of the red-green blind, who confuse these colours and do not show the characteristic bipolarity in sensitivity to them. Thus, in the red anomalous the point of change over from red to green in the red-green axis is deviated strongly to the red side, and in the green anomalous to the green side, and in addition the directions of these axes are different. In the red-green blind the " point " of change is extended into a greatly exaggerated threshold, so that in the worst cases the distinction or bipolarity of red and green is altogether lost, and in the moderate cases it is vastly weakened. No other theory could account for these facts as adequately as that of Houstoun.

It is an important point that for the red-green blind subjects red and green were positively correlated and appeared as co-variants in the second bipolar factor. This shows that the negative correlations for colour weaknesses were not produced purely by the technique of testing colours in pairs of opposites or complementaries. Where this technique is employed and colour vision is normal or anomalous, strong negative correlations appear, and result in heavy weightings in the appropriate bipolar factors. With the same technique, but with the highly abnormal vision of red-green blind subjects, the correlations are positive although the colours correlated are still measured as opposites. Hence it is legitimate to infer that the nature of colour vision rather than the form or technique of the test produces the negative correlations where they do appear.

ANALYSIS OF COMBINED CORRELATIONS

In order to make the best possible use of the data, combined inter-correlations were calculated by Fisher's " z " technique for all the tests of red, yellow, green, blue and their brightness levels so far reported. These were then factorised approximately by the simple summation method, with the results shown in Table 72 for normal and in Table 73 for red-green blind subjects. The factor loadings serve to substantiate the patterns found in the nine-colour experiment. Normal subjects show a general factor, followed by a red *versus* green and then by a yellow *versus* blue factor. Colour-blind subjects show a general factor followed by a blue *versus* yellow and then by a red+green *versus* blue+yellow factor. It is interesting that these results should be obtained in spite of the several different techniques, and the various coloured papers, and polychromatic and monochromatic filters which were used, but combined results of different tests have generally been avoided in this research.

Motokawa's work on the recovery of electrical excitability of the eye following stimulation of the retina with monochromatic lights,[3, 4] gives strong support to the view that yellow is based on an independent receptor process, but he found that the green process was specially weak in certain deuteranomalous subjects, and missing in

TABLE 72

FACTOR LOADINGS FOR COMBINED INTERCORRELATIONS: NORMAL SUBJECTS, 520 FOR COLOUR AND 402 FOR BRIGHTNESS

Colour or Brightness	Factor Loadings		
	I	II	III
Red	·165	+·496	+·404
Yellow	·311	−·416	+·478
Green	·107	−·539	−·426
Blue	·194	+·411	−·542
Brightness	·252	+·148	+·096

a deuteranope, while the red process could not be found in a protanope. More detailed statistical data would be necessary, showing the variability of the retinal processes among numerous subjects of different types, before his conclusions could be related clearly to the results of the present research. Factorisations give generalised

TABLE 73

FACTOR LOADINGS FOR COMBINED INTERCORRELATIONS: RED-GREEN BLIND SUBJECTS, 61 FOR COLOUR AND 42 FOR BRIGHTNESS

Colour or Brightness	Factor Loadings		
	I	II	III
Red	·638	−·398	−·105
Yellow	·544	−·471	+·288
Green	·544	−·133	−·266
Blue	·449	+·628	+·194
Brightness	·486	+·364	−·126

results of many subjects taken together. Motokawa's observations apply to particular individuals whose relationships to the norms are not known. He points out, however, that in some deuteranopes a rudimentary green process was found, and suggests that his method might prove to be useful in measuring the magnitude of the defects of different subjects.

BRIGHTNESS LEVELS

Table 74 summarises the correlations between brightness levels and the various factors in the experiments reported up to this stage. It appears that brightness level correlates positively with the general factor throughout, and apart from this its most marked correlations are with the green side of the red-green factors and with the blue

TABLE 74

CORRELATIONS BETWEEN BRIGHTNESS LEVELS AND COLOUR FACTORS

Tests	Subjects	CORRELATIONS WITH FACTORS				
		General	- Red	Green	Yellow	Blue
Combined Tests	Normal	+·252	+·148	—	+·096	—
	R-G blind	+·486	—	+·126	—	+·364
Nine-Colour Tests	Normal	+·171	—	+·074	—	+·244
	R-G blind	+·424	—	+·026	—	+·635
	R-Anom.	+·228	+·219	—	—	+·333
	G-Anom.	+·774	—	+·535	+·093	—

side of the blue-yellow factors. This fully accords with the following general observations : when red loses saturation, owing to red-green defect, except for protanopes and some red anomalous subjects, it tends to be confused with a relatively bright orange or yellow; when yellow loses saturation, again, it does not tend to lose brightness, but becomes confused with a bright grey or dull white; green, however, tends to be confused with greys on a rather lower level of brightness for the green anomalous; finally, when blue loses saturation it is darkened and tends to be confused with dark grey or black. These observations might accord with Hering's theory.

From the point of view of colour vision theories this is very interesting. Brightness level must be determined mainly by general sensitivity to light, apart from differential sensitivities to particular hues. This is shown by its consistent positive correlations with the general factors. It leads to the inference that there must be a special set of responses to brightness, and that these are possibly the same as the responses to light in general apart from colour. Indeed, it might be found that the general factor represents a combination of brightness discrimination and of the composite ability to carry out the tests according to the instructions given. In addition, brightness is partly determined by all four types of colour response : red and yellow carry positive contributions to brightness, and green and more

particularly blue add to brightness when they are saturated, but diminish it when they lose saturation owing to defect of hue sensitivity. For protanopes, however, loss of sensitivity to red reduces brightness, but not for deuteranopes.

The most important relationship of brightness is with general sensitivity to light. This could be explained in terms of a special brightness determining system, as in Hering's theory, which might be bipolar, as he suggested, but is perhaps more likely to be unipolar. The apparently bipolar nature of black-white vision is found in the well-known phenomena: (a) simultaneous and successive brightness contrasts; (b) the intermediate dark grey or " self-light " of the unstimulated retina; (c) the intense positive sensation of blackness which occurs when retinal stimulation is suddenly cut off and which rapidly gives way to the familiar mid-grey; (d) the opposite phenomenon of intense brightness which occurs when retinal stimulation suddenly replaces absence of stimulation, and which, again, rapidly reverts to an experience of moderate intensity. It is not possible to stimulate the retina with " pure " white, grey or black, as no such light rays exist. The physical stimuli corresponding to white and grey must be composite. The extremest black and white experiences might be responses to situations, in the Gestalt sense, rather than to simple stimuli, because they are only produced as contrast effects. The bipolarity of the black-grey-white series might therefore be reduced to a monopolarity of stimulus and response, in which the presence of mixed light rays (or of rays unmixed but not differentiated for hue by the receptors) was the positive stimulus, and in which the absence of the stimulus corresponded to darkness, or no sensation. Then the intrinsic or self-light of the retina, the mid-grey which was the neutral position of Hering's bipolar black-grey-white series, might be due to the relatively infrequent and spontaneous discharges of red, green, yellow, blue and brightness receptors in approximately equal numbers.

INTERPRETATION OF THE FACTORS

In view of the interesting part factorial analysis has played in the foregoing discussion, it may be worth while to make some further observations on the nature of this statistical method and on the status of the factors revealed. Burt has pointed out to me that " a factor-analysis as such is merely a mathematical device for reducing a given table of correlations to a standard form, i.e., to a form in which the correlations relate, not to correlated tests, but to

uncorrelated factors, the uncorrelated factors being extracted in order of their contribution to the variance ".

In non-mathematical language it may be said that factorial analysis is simply a method of reducing a complex table, the figures in which express the inter-relationships of a given group of tests, measurements or observations, to terms simple enough to be interpreted. It enables us to see and grasp clearly the essential trends of influence in our experimental results, and is a step towards eliminating the unessential, and drawing conclusions of a generalised character. These are dependent upon and must be relevant to the nature of the experiments or tests with which we started. Factorial analysis will not produce definite results by magic out of an inefficient or incompetent experiment or test, nor does it conjure up realities which are independent of ordinary methods of experiment, observation and inference. It inevitably eliminates all individual peculiarities, which are none the less important for scientific psychology.

The factors found in the analysis of the results discussed here must be interpreted in terms of the problems to be solved and of the experiments designed to throw light upon them. A general factor was found for each table of correlations. This represents the ability of the subjects, on the average, to do the tests, when variations of sensitivity to hue are excluded, and such an ability, though it is independent as a factor in the analysis, may be highly complex as an ability. The occurrence of any single and independent factor is not necessarily evidence that it is psychologically or physiologically ultimate and unanalysable.

When the general factor has been eliminated, the remaining factors represent the subject's ability to distinguish the colours employed in the tests. These abilities take the forms of red-green and yellow-blue bipolar processes or functions, except for the red-green blind subjects. In the normal the red-green factor contributes more to the total variance than the yellow-blue factor, but in all classes of red-green defectives the yellow-blue factor contributes more. This fully accords with the general observation mentioned on previous pages, that for normal subjects the distinction of red and green is much sharper than that of yellow and blue, and dominates colour discrimination. For red-green defectives it is well known that the yellow-blue distinction is dominant, and this observation has led to their being called " dichromatic ", though in fact very few of them are strictly limited in this way. For the red-green blind, these two colours are combined against blue and yellow in the second or minor bipolar factor. This shows that the red-green functions are

not lost for them, as the upholders of the Young-Helmholtz theory have often claimed, but are working together rather than as an opposed pair.

It is important that the order of the bipolar factors should vary according to known variations in the nature of colour vision. The number of normal subjects tested was perhaps not sufficient for confident inference of a second bipolar factor; of anomalous and colour-blind subjects the number was certainly not sufficient according to ordinary statistical standards. The groups of subjects, however, were distinct from each other, and each was a coherent group in itself. Thus the factors extracted may be viewed as indicators, though not all statistically significant in the usual way. If it were doubted that the second bipolar, or yellow-blue factor of the normal subjects, was more than a sum of errors, then the consistent appearance of just such a factor as the first bipolar in the red-green defectives fits in admirably with the known differences in their colour vision from that of the normal subjects, and confirms the presence of a yellow-blue factor other than error in colour vision in general. It is the consistency and appropriateness of the patterns of factor loadings and their changes according to the nature of the defect which is of interest, rather than their actual weights. The presence of a clear yellow-blue factor in the red-green blind subjects, who are known to have good blue-yellow vision, and the characteristic form of the red-green factor for them, also confirms the view that yellow and blue are in the nature of a bipolar pattern in colour vision. In other words, the factorial analysis of the sensitivities of all these groups of subjects confirms what is known of colour vision and what might be expected on a theory such as that of Houstoun, and it throws additional light on the whole subject, because it makes the distinctions between the different groups of normal and abnormal subjects clearer than before. The analysis, however, is only a series of mathematical steps towards scientific inferences, and the factors revealed may be highly complex in psycho-physiological nature. Their detailed organisation still remains to be revealed by further work, and a hypothesis, such as that of Houstoun, serves as a guide along the path of scientific research.

The Over-Lapping of the Receptor Systems

An interesting inference may be drawn from the factorial analyses of the results of the experiment just described. It may also be drawn, though less definitely, from the four-colour tests mentioned in

previous chapters. In general, the bipolar factors tend to divide the colour circle into opposed halves. On the physical side, using the monochromatic filters, the only colour which includes any other colours to a marked extent is purple. The amount of over-lap in the transmission bands of the neighbouring spectrum colours is negligible, and in the bands of separated colours, such as blue and green, is non-existent. Thus we can say that large over-lap on the psychological side corresponds to homogeneous light stimuli which do not over-lap on the physical side. The psycho-physical response " red " is stimulated by light ranging almost from blue to yellow, though principally by red light rays. Similarly, " yellow " is stimulated by light ranging almost from red to green; " green " by rays ranging almost from yellow to blue; and " blue " by light rays ranging almost from green to red. Hering's coloured diagram given by Myers,[2] which is modified in the Frontispiece of the present book, and which shows these over-lapping psycho-physical primaries, is justified by detailed research.

On the psycho-physical side none can say what is the nature of " g " or general intelligence, and most of the other unique functions found by factorial analysis, such as general emotionality or the aesthetic and technical factors in art appreciation[5], have no strictly physical counterparts whatever. General intelligence is an ability or " faculty " rather than a directly measurable object. In colour vision, however, although we do not know the intimate nature of the psycho-physical basis of sensitivity, we do know in precise detail the physical nature of their appropriate stimuli. This throws some useful light on the principles of factorial analysis, because in no case has it been necessary to rotate any of the factors in order to find an intelligible interpretation of them. They are readily interpreted in their simple forms, and show a direct and obvious bearing upon the nature of the physical tests employed and on what was already known of colour vision and its defects in the subjects tested. Thus Burt is supported in his plea that rotation is not generally necessary in factorial analysis. It is remarkable that even the brightness levels were readily included in the factorial analysis, and their loadings corresponded with what was known from general inferences about brightness in relation to colour sensitivies. It sometimes appears as if violet were more likely to be a primary than blue, but the violet colour filter was the least monochromatic other than the purple, and included the blue to a certain extent, hence the appearance of violet as if in a primary position is possibly misleading.

The Frontispiece

The coloured Frontispiece is a diagram to illustrate five general types of colour vision on the four-colour theory. It corresponds approximately with the results of factorial analysis for normal, red-green blind, red and green anomalous colour vision, and also indicates the way in which marked yellow-blue weakness differs from the colour vision of the normal subjects. Owing to the difficulties of representing brightness variations in addition to colour on a two-dimensional diagram, the differences between deuteranopes and protanopes, and between red anomalous with and without darkened red, have not been represented.

Figure I in the Frontispiece is modelled on Hering's famous diagram which is reproduced by Myers, as mentioned above. Hering and Myers, however, represent the proportional extents to which assimilative and dissimilative changes and the corresponding sensations are supposed to be excited by various primary, intermediate and mixed light stimuli. Thus orange is excited by a moderate degree of dissimilation in both the red-green and yellow-blue systems, and is consequently red + yellow from the point of view of the receptor mechanism. Purple, however, is excited by a dissimilative change in the red-green but an assimilative change in the yellow-blue system, and is therefore red + blue in terms of receptor process. In the beautifully printed colour circle which accompanies their four-colour diagram, Hering and Myers showed the effects of these combinations. In their four-colour diagram, however, they showed the proportional contributions of red, yellow, green and blue as if equal in normal colour vision. This is not supported by the results of factorial analysis, or of the general consideration of colour phenomena, in the present research. Red and green contribute far more to normal colour vision than yellow and blue, as explained in the previous section. Figure I in the Frontispiece has therefore been changed from Hering's diagram to show the predominance of red-green over yellow-blue contrasts in normal colour vision.

Figure II shows the predominance of yellow-blue over red-green contrasts for the red-green blind. Two comments are necessary : firstly that no attempt has been made to show the darkening of red in protanopes, and so the figure applies equally well to protanopes and deuteranopes. Secondly, this research shows that protanopes and deuteranopes are both widely varying classes of individuals, and it is therefore impossible to give a single diagram which does adequate justice to all their variations. In some the red-green components of

colour experience are almost completely absent, in others fairly large. In order to represent their differences fully we should need a whole series of coloured diagrams in which there were various degrees of loss of red and green in comparison with yellow and blue, and also a third dimension to show the darkening of the red in protanopes, which is also variable.

Figures IV and V show the relative losses of green and of red as components of colour experience in the corresponding types of anomalous subjects. Here again, no account has been taken of the darkening of red in certain of the red anomalous group, or of the variability of individual defects. Lastly, Figure III shows the diminution of yellow and blue relatively to red and green in the yellow-blue weak. These are not called yellow-blue blind for reasons already explained, but it is instructive to compare Figures I and III and to see that a person who has a loss of yellow and blue will be even more predominantly affected by red and green in his colour experiences than a normal subject. Again, no account has been taken of the darkening of violet often found in yellow-blue weak subjects, or of the marked individual differences between them, which could be represented only by a large series of coloured diagrams.

Before leaving this subject, it should be added that these figures may not be strictly comparable in theoretical meaning with the Hering-Myers Diagram. The latter showed the relative proportions of assimilative-dissimilative changes. These figures show the relative contributions of red-green and yellow-blue contrasts in colour experiences. The difference between normal and colour-blind vision is produced by the reduction in efficiency with which the red-green (or the red and the green) receptors respond differentially to red and green stimuli. This relative loss of discriminating power is felt in the increase of yellow-blue over red-green contrasts. The figures therefore represent discriminating power rather than assimilation-dissimilation, though they might be thought of in this way if we wished to support the Hering theory in its old form. The same applies to the figures showing anomalous colour vision, with appropriate changes, and also to the colour vision of the yellow-blue weak in Figure III.

A SPECULATIVE RECONSTRUCTION

In order to grasp more clearly the kind of inferences which can be drawn from the factorial analysis discussed in previous paragraphs, it would be instructive to consider the following speculation.

Suppose that all mankind were totally colour blind, able to see only the differences in brightness now perceptible to us in the spectrum, and not able to distinguish any colours at all, except in so far as shades of white, grey and black may be called colours. Suppose, in addition, that we had been able, by scientific research, to make the colour filters used in these experiments, though unable to see the different lights transmitted by them ourselves as different colours, but basing our work on researches upon purely physical criteria for differentiation between them. Suppose that certain animals, such as the higher apes, were able to see these colours, and that we had been able to carry out the experiments described in this book on those animals.

Then the results of the experiments would represent differences of perception among these animals which did not correspond to any experiences of our own except in terms of brightness. Under these hypothetical conditions it would be easy to interpret the general factors found in analysing the four tables of intercorrelations. We should say that they represented abilities to carry out the tests in terms of brightness sensitivities. The bipolar factors, however, would be very puzzling to us. We should be led to frame a hypothesis dividing our colour filters into four over-lapping groups, and might call these groups A, B, C and D, each group including several filters, in such a way that group A and group C included all the filters, about half being in A and the other half in C. Similarly groups B and D would divide the filters between them, but cutting directly across the A—C grouping. These patterns would vary to some extent with the peculiarities of the experimental animals. The vast majority (about 93%) would give a grouping in which the bipolar factors set off group A against C in the first place and group B against D in the second place. We should call this " normal " because it is most frequent. A small proportion of the animals (about 4%) would give a wholly different pattern of bipolar factors, in which groups B and D were set off against each other in the first place and a combination of A with C was set off against a combination of B with D in the second place. A third set of animals (about 3%) would give a different pattern again, in which the colour filters in groups B and D appeared as contrasted in the first bipolar factor and those in A and C in second bipolar. This set of animals would be sub-divided into those which did and those which did not show a special negative loading for the central member of the A group of filters.

Further consideration of the overlapping groups of filters would lead us to suppose that they must correspond to four specialised

modes of vision, in each case most satisfactorily represented by the filters which were most nearly central for each of the groups A, B, C and D. We should therefore pick out four special filters, one characteristic of each group, and call these four by special names, for instance the a, b, c, and d filters. These four filters we should then tend to class together as of primary importance, while the other filters we should class as secondary or intermediate, because they were not central filters in their groups. In addition, we should classify our primary filters into two sub-groups, the a—c and the b—d classes, and say that these sub-groups corresponded to independent functions, adding that the sensitivities in each pair must be related in a bipolar or opposite manner, giving rise to negative correlations in the tests (except where the A—C defective subjects were concerned) and consequently to bipolar statistical factors in the analysis. Then we should be led to formulate a scientific hypothesis about sensitivity to light in our animal subjects. It would correspond exactly to the requirements of Houstoun's theory, and it would not correspond at all to those of the Young-Helmholtz, Ladd-Franklin or Edridge-Green theories.

If at this point we suddenly became sensitive to colours ourselves we should at once identify the A, B, C and D groups of filters with the reds, yellows, greens and blues in the spectrum, and we should see that the primary filters a, b, c and d corresponded almost exactly to pure red, yellow, green and blue, while the secondary or intermediate filters corresponded to colours like orange, yellow-green, blue-green and violet, which appear composite or subjectively analysable.

Thus it is possible to reconstruct the whole discussion of colour vision and its problems in " objective " language, as if no person involved in the research himself had any direct experience of what he was investigating. This is, of course, exactly what does happen in many forms of scientific research, but psychology is always in the peculiar position that much of what we study is part of our own consciousness. This is not an invariable rule, of course, because if an extreme protanope did research on colour vision, he would be compelled to accept most of his subjects' statements that there was a difference between purple and violet, and, similarly, those of us who are " normal " have to learn to accept some of our subjects' statements that there is no such difference. It is an evasion of reality to try to convert psychology into a purely " objective " science, though the introduction of objective methods into psychology has been of great value, and their importance as parts of its procedure cannot be denied. In the study of colour vision this is clear enough

and it is evident that the satisfactory way in which objectively gained and analysed data fit in with direct experience turns out to be one of the strongest links in our theoretical chain.

The psychology of colour-vision defects might be compared with the clinical study of wooden legs. We might tabulate the various dimensions of wooden legs, their lengths, diameters, numbers of joints, weights, strengths in compression, tension and shear. These results might be studied by the analysis of variance, or intercorrelated and factor analysed, and the outcome of different forms of statistical analysis and comparison would be most valuable. They would, however, tend to leave out of consideration one of the most important points, namely, the study of how people use wooden legs. This study would show that each person had his own peculiar mode of adaptation to the effects of injury. Just as some one-legged men can walk better with the aid of a stick alone than others with the help of the most elaborate artificial limb, so it happens that some extremely colour-blind men have made a better adaptation to their defects, and less often make errors in daily life, than others who are much less colour blind. Probably Edridge-Green is the only writer since Goethe who has grasped the significance of this side of the study of colour blindness, but in the present volume a serious attempt has been made to couple the predominantly statistical emphasis with clear accounts of the colour vision of individual defectives. The science of psychology can never be reduced to a series of frequencies, deviations, averages, and mathematical generalisations. It will always call for a consideration of how the individual lives in relation with other people and the material environment.

RED-GREEN DEFECTIVE SUBJECTS AS INDIVIDUALS : PROTANOPES

Six extreme protanopes were found : four men and two women. The first was a member of a psychology class, and he had a difficulty with the Collins-Drever Group Test of Colour Blindness when it was applied to the whole class, though he could read the figures when it was close to him. On careful testing he proved to be an extreme protanope. He was better able to distinguish red from yellow than from green when the brightness levels were equated for him. In the yellow-blue test he had a very large range, calling blue " green " and failing to distinguish yellow from grey of equal brightness. In the other three tests he gave intermediate results. He reported that for many years he thought he was "colour ignorant", and that his difficulty was in the use of colour names rather than in distin-

guishing hues. He knew that he confused greens with greys and pale blues with pinks. He said he distinguished colours mainly by their brightnesses, and at this he was most expert : dark colours would be reds or blues, bright colours would be whites or yellows and intermediate colours greys or greens. By other forms of half-conscious guidance, gained from shapes and names of familiar objects, from surface texture, situations and uses of objects and from the remarks made by other people, he would be able to pass for having good colour vision in ordinary circumstances. He was a very highly intelligent man and took a special interest in analysing all these points in detail and explaining them.

The next extreme protanope came with three sisters, two of whom were also extreme protanopes. They had a Latvian father and English mother, and their father and father's brother were known to be colour blind. Their mother was believed to be normal, and nothing was known of any defectives on her side of the family. There were four red-green blind sisters, two normal sisters and two colour-blind brothers in the family; one of the sisters had a colour-blind son. Those members of the family who were not tested were inaccessible abroad or too old to be asked to do the tests. Colour blindness was regarded as a " family gift ", and all of them were in the habit of causing their friends great amusement by their mistakes. This man had extremely darkened red and was wholly unable to distinguish red, yellow and green of equal brightness, or perhaps it would be better to say equal darkness. He was well aware of his defect, and he knew for instance that he had to have the brown ball specially marked for him at snooker. He was a picture frame-maker, and knew that he tended to confuse " ebony " with " rose-wood ". He knew that the tram-car which took him home was green because it went along Paisley Road—which was one of the " green " tram routes in Glasgow at that time. He was normal in yellow and blue.

·His two sisters who were also extreme protanopes, with greatly darkened red, were unable to distinguish red, green and yellow of equal darkness. The first knew that she must keep to blacks and browns in her dress if she was to avoid what other people called " clashes ". When she came to the laboratory, however, she was wearing a black coat and a reddish brown scarf, which she thought black, and was greatly amused when it was pointed out to her that they were not the same colour and that the combination seemed a trifle odd. She knew that she could not tell green from brown, but thought she could distinguish red and black, though she knew

she confused royal blue with purple and greenish blue. She thought she used to be more defective, but no doubt the difference was due to acquired skill in using brightness differences and other secondary guides to colour, because she could not have been more extremely red-green blind. She had been a dressmaker, but lost her post because she stitched a pale blue frock with pink thread. In parting she remarked that she could see colours perfectly well but did not know their names, and laughed heartily about the whole matter.

The second sister was much the same. She had served in a hat shop, but sold a lady a purple hat to match a blue dress and so lost her post. It would be interesting to know whether the lady who bought the hat was also colour blind. She had also been a cinema attendant, and a tram conductress, and had to identify the different priced tickets by number and not by colour, because the red, green and yellowish tickets looked exactly alike to her, and the blue ones looked pink. The third sister was generally regarded as the most normal member of the family besides the mother. She had great difficulty with the Ishihara test, however, and admitted that she was inclined to confuse purples and pinks of a dark tone. In the colori-meter test she proved to have a decided red-green weakness, with a red deviation, and it is highly probable that she, her normal sister not tested and her mother, were heterozygous for protanopia.

A very interesting subject was the only moderate protanope in this experiment. She had been tested previously by Professor W. J. B. Riddell. She had a moderate red-green range, with a small red devia-tion and very darkened red. She was very slow over the Ishihara test, probably knowing that it would show up her weaknesses, and in spite of her caution she failed on 20 out of 24 plates, but was under the impression that she had read them all correctly and was inclined to think that it had proved her to be normal, while the colorimeter test she took to be in error when it showed her to be defective. Hence it was necessary to agree that she was " very good at colours ", which, considering the magnitude of her defect, was perfectly true. If we could measure their ability to distinguish the colours they do see, apart from their actual defects, it would often be found that the colour blind are much more expert than the normal. She admitted no difficulties in daily life, but said she bought a pair of stockings which her sister called " purple " and she thought were grey. She had different ideas about green and blue from other people, in her opinion. Other members of the family, except her brother, had been tested with the Ishihara test and showed no defects. She had darkened red, darkened violet and darkened green, and was very

yellow-blue weak indeed, as well as being moderately red-green blind. From the point of view of heredity it is interesting to consider how her red-green defect was gained, because her father and mother both passed the Ishihara test. Her mother might be heterozygous, but this would not account for her being red-green blind, unless her father could supply a defective gene as well. Suspicions might be raised that she had an hysterical exaggeration of a slight defect which was a heterozygous condition inherited from her mother. She was almost a link between the ordinary protanope and the most red-green weak of the normal group, of which the most extreme woman had a red-green range of 7 mm., while her range was 11 mm. The subject with a 7 mm. range just passed the Ishihara test, while the present subject, with an 11 mm. range failed. Since she had only a very small red-deviation she is not a link between the red anomalous and the normal or between the red anomalous and the extreme protanope. Several men had 8, 9 and 10 mm. ranges and may be viewed as bridging the gap between colour weak and colour blind to a certain extent.

Later it will be seen that on the two locus theory of the inheritance of colour-vision defects, a man may be a double defective in genotype, or genetic constitution, and probably at least nine such genotypes are possible. Some or all of them may be normal in phenotype, or manifest condition. Thus a man who has apparently normal colour vision might marry a woman who is a normal heterozygote, and have a major defective daughter. In this case, for example, the father might have genes for protanopia and deuteranopia in different loci on his X chromosome, and the mother might be a normal heterozygote for protanopia. Then both parents would possibly pass the Ishihara test, but the daughter could be a protanope—she would be homozygous for protanopia and heterozygous for deuteranopia at the same time.

Red-Green Defectives as Individuals : Deuteranopes

One man was a very extreme deuteranope, but had no defect in yellow or blue, but called all degrees of saturation of red and green "red", a term which he also applied to yellows. He had noticed a difficulty only since becoming an adult, though when he had a lesson on "colour" at school he found that all members of the class understood it except himself. He considered that he was not colour blind but was uncertain of greens and browns, especially at a distance. He was also uncertain of red or green signals at a distance,

but not if near, and could see ripe rowan berries if he was close to them. He thought he could see a contrast between a yellowish apple and the leaves of the tree, and he thought other people did not notice this difference. Though he believed he could distinguish all primary colours, he failed to see the differences between the Belgian and French flags at a distance. He had no difficulty with the traffic lights, but regarded the yellow as a brighter red, and the green as a light red which was nearly colourless.

His wife and family liked him to approve of coloured clothes which they bought, and regarded him as a particularly good judge. It is not difficult to see how an illusion of this kind can arise. The red-green blind is often exceedingly fussy over colour matches, and will hesitate very thoughtfully for a long time where normal people would adopt a confident and " off-hand " attitude. He rejects nearly all possible matches for fear of making a mistake, and hence gains the name for being an exceptionally accurate judge of colours. At the same time, he does not reject any colour matches which a normal person would accept, and so, in the end, he may give the impression of being far more particular than the normal person with whom he is co-operating in arranging colours.

He had a colour-blind brother, who classed a flower as " blue-family " when other people called it purple. Two other brothers were perfectly normal. In a painting of a woman and a cat sitting by a fire which he had copied, the present subject made numerous errors such as the following : a dull orange shawl—yellow; orange-red flames—red; fawn markings on the cat—red; greenish yellow stone —red; dull yellow shadows on the woman's cap—reddish; greenish-blue fields—pink-red; fawn or brown shadows inside the window— pinkish red; pale brown inside the window—lime green; yellowish red edges of flames—bright lime green; dull red flower pot— green; olive green leaves—blue-green; pink flowers—green; blueish pink shadows on face—olive green and rose; blue cup and saucer—yellow with white rims; brownish yellow table-top— yellow with blue shadow; dark brown and yellow chair legs—black and grey; violet sleeves of apron—bright blue. These errors indicate the sorts of mistakes an extreme deuteranope might make in painting, if he is very cautious. If he was reckless he would make far greater errors. This subject was most anxious to be helpful in a scientific study, and so were his two daughters, who came to be tested and both of whom showed slight red-green weaknesses, and both must, of course, according to the principles of sex-linked inheritance, have been heterozygotes.

The moderate deuteranopes were specially interesting, because some of them seem to bridge the gap between the ordinary deuteranope and the colour weak, while others seem to bridge that between the deuteranope and the green anomalous. The largest range for green anomalous subjects was 2·0 mm., while the least weak of the deuteranopes had a range of 8·0 mm. The matching point of the green anomalous varied between 26·5 mm. and 28·5 mm., while the moderate deuteranopes varied from 20·5 mm. to 28·0 mm. Hence the distinguishing features of the green anomalous were consistent smallness of range and consistent largeness of deviation, while the moderate deuteranopes had never less than four times the range of the anomalous and their deviations, though sometimes equally great, varied between limits nearly four times as wide. The same contrasts were found between the red anomalous and the moderate protanope. The biggest range among the red anomalous was 3·0 mm., while the least range among the protanopes was 11·0 mm. The matching points of the three red anomalous men varied between 10·5 mm. and 12·0 mm., while the only moderate protanope in this series had a matching point of 20·0 mm. A moderate protanope with a very large deviation will be mentioned in another chapter.

One deviant deuteranope with a decided yellow-blue weakness and a yellow deviation, was a telephone engineer. The experimenter noticed that he had the peculiar " sheep's eyes " not infrequently found in deuteranopes and asked him if he had ever had any difficulty with colours. He was amazed, and replied that he was colour blind, and added that he could not distinguish red and brown telephone cables, though he had no difficulty with traffic lights.* He classed brown beads with red, which is more characteristic of protanopes than of deuteranopes, but there was no suspicion of darkening of the red in his vision. Orange and yellow beads he placed together, but gold he put with green and blue-green with blue. He failed outright in the Ishihara Test. He had a large deviation but a range 5·5 times as great as any range found among the green anomalous and accepted the normal equation easily, so he was not an intermediate between the colour blind and the anomalous. He was much interested in the tests, and suggested an experiment with Vitamin A. He took two tablets of Alvoleum (a dose of 4500 International Units of Vitamin A) *per diem* for a fortnight, and then came to be re-tested. There was a slight improvement, which might have been due to skill in doing the test rather than to any change in his colour vision. Then he took no more Vitamin A for another fortnight, and was again

* Later it was found that his daughter's eyes were similar and that she was also a deviant deuteranope.

re-tested. Again there was a slight improvement, probably due to practice. The three results are shown in Table 73. It will be seen that he becomes more and more like a green anomalous subject in the red-green test, and the yellow-blue results change least, while the other three tests all show improvement. The subject was consciously trying not to exploit increasing skill in doing the tests, but admitted that it was to some extent unavoidable. In the beads and Ishihara tests he also showed improvement, more in the beads than in the Ishihara. It is interesting that the red-green deviation remained (or actually increased) while the range diminished.

TABLE 73

REPEATED TESTS ON A DEVIANT DEUTERANOPE, AT INTERVALS OF TWO WEEKS, WITH 4500 INT. U. VITAMIN A *per diem* BETWEEN THE FIRST AND SECOND AND NONE BETWEEN THE SECOND AND THIRD TESTS

		R-G	O-BG	Y-B	YG-V	P-G	
First	Match	25.0	21.0	25·5	15·0	23·5	in millimetres
	Range	11·0	11·0	10·0	1·0	10·0	,,
Second	Match	25·0	14·0	24·0	18·5	26·0	,,
	Range	9·0	3·0	11·0	4·0	11·0	,,
Third	Match	28·0	15·5	25·0	17·0	23·5	,,
	Range	5·0	4·0	11·0	3·0	8·0	,,

This suggests that great deviation, when present, is a more obstinate defect than large range, and possibly therefore more fundamental in some way, but many more tests of a similar kind should be done with moderate deuteranopes and also protanopes, including subjects with and without large deviations, to see in what ways practice and also perhaps vitamins might change their colour vision.

It is interesting to note that this subject was picked out on account of his peculiar " sheep's eyes ". In the same evening class the writer also picked out a girl for the same reason, and asked her whether she had any difficulty with colours. She had two deuteranope brothers and her maternal grandfather was also colour blind, but it is not known how far " sheep's eyes " are associated with deuteranopia.

RED-GREEN DEFECTIVES AS INDIVIDUALS : ANOMALOUS SUBJECTS

Eleven green and three red anomalous subjects took part in this experiment, and only two of them were found by chance : a green anomalous woman and a red anomalous man.

Three green and one red anomalous subjects were tested on the

same day. The first had been rejected for air-crew work by the R.A.F., although he had no difficulty in daily life and no suspicions of colour defect himself. He had previously been tested and passed by a medical officer, using the wools test. He had no known colour-defective relatives. He made not a single correct response out of twenty-four Ishihara plates. The second had also been tested and failed by a R.A.F. tester. He had no colour difficulties so far as he knew, and objected to the R.A.F. test. Then he was re-tested and classified as " defective-safe ". This happened three times. He made four correct readings out of twenty-four Ishihara plates. The third green anomalous man also knew of no difficulties himself, but was failed by the R.A.F., though his brother was passed. He made three correct readings in twenty-four Ishihara plates. The fourth man was red anomalous and had been tested four times by the R.A.F. Three times he was classed as " colour safe " and once failed. All four men had been most puzzled by being failed in the R.A.F. tests. They came to the laboratory in the hope of gaining some insight into the nature of their defects. The writer explained the position to them as clearly as possible. He told them that their performance in the Ishihara Test was worse than that of many moderate deuteranopes and protanopes who actually knew that they were defective because they made obvious colour confusions which the present group did not make. On this ground alone a conscientious tester would have no alternative but to fail them, unless he had other and more satisfactory means of discriminating them from the colour blind, which, in the present state of tests, was not available to the R.A.F. If the Ishihara Test was the main, and possibly the only guide, the tester would be forced to classify them as " totally green (or red) blind ". Their per-formance on the Edridge-Green Lantern Test, which had been used for the man who persistently claimed a re-test, would also be am-biguous, and so would the Holmgren Wools. At the time the Ishihara Test had the greatest prestige, and was generally accepted as that nobody clearly grasped its faults. It was a crude cut-out which could be relied upon to detect all who might be suspected of a major weakness in red and/or green.

This brought up the next point: namely that the Ishihara Test grouped the anomalous indiscriminately with the colour blind. Even when a fully adequate test was used, these anomalous subjects would still be classed as major red-green defectives, and the question would have to be raised whether in fact they would not be more, rather than less dangerous than the red-green blind, because they did not know they were defectives, or that they were liable to make colour

judgments so different from those of the normal that they must be classed as " gross errors " for practical purposes. A green anomalous man, confident of his colour discrimination, might think that a light which the normal called green was pale red or yellow; a red anomalous man might think a light pale green when the normal called it red. This was demonstrated beyond any possible doubt to them with the colorimeter. Such a mistake at sea or in the air on a foggy or snowy night might lead to a disastrous accident : none could deny it.

The final point was raised by the men themselves : if their colour discrimination was good in itself, why should they be classed as red-green defectives ? The answer to this is essentially statistical, but it is different from the answer, for instance, to the question why a person with an Intelligence Quotient of eighty should be considered as below normal. The red or green anomalous is a defective because his colour judgments, although they show good discrimination as far as he is concerned, differ in important ways from those of the normal—and his abnormality is simply the fact that not more than about 5% of men and less than one woman in about 250 would agree with him. In consequence, if he had to work with colour signals adapted to the majority, he might be liable to make " mistakes " from the point of view of the majority. The statistical reason why a person with an Intelligence Quotient of eighty is below normal is different, but is essentially the same as the reason why the colour blind rather than the anomalous are abnormal : it is that he has a measurably lower ability than the majority in the function in which he is being tested, intelligence or colour discrimination, accordingly.

In the absence of an adequately conducted and decisive scientific research, showing that the anomalous would not be dangerous in the way described above, the R.A.F. had been right in rejecting them, although the Ishihara Test had been wrong in classing them as colour blind. Three of them called a given spot of colour " red ", the fourth called it " green ", and the writer who knew that his colour vision agreed with that of the majority, said it was a perfect match for the standard spot which was " yellow ". As red, green and yellow (or " white ") are the most frequent colour signals, there was nothing more to be said. They went away satisfied.

There were two green anomalous women in this series of subjects, one of whom was found by chance. She was an art student and had never noticed any peculiarity in her colour vision, except that she had sometimes wondered whether some other people had what she called " a different scale of colours " from her own. She was most surprised at the result of the test, but as she came with a friend who

was normal, they were able to discuss it together. They found, as usual with anomalous subjects, that a spot which was red to the anomalous could be green to the normal.

If the whole population were red-green blind the distinction between red and green would be in endless dispute; some would be sure that there was such a distinction, others confident that there was not, and still others would be uncertain, just as it is with the distinction between blue or violet and indigo to-day. If the whole population were green or red anomalous, the position would be quite different. The distinction between red and green would never be in dispute, nobody would doubt that it existed, but the red anomalous and the green anomalous would never be able to agree about the exact way in which to distribute known reds and greens into the two classes: " red " and " green ".

The details about three red anomalous subjects suggest that they are a homogeneous group, like the green anomalous, but slightly more variable. The most interesting point is the discovery that only one in these three had the red end of the spectrum darkened. This has an important bearing on theories of colour vision, because it would be impossible on the Young-Helmholtz theory, according to which weakness of red and darkening of red must inevitably go together. It is true, of course, that in the green anomalous we should expect green to be darkened, according to this theory, and it is not; but this is a less decisive point because green lies in the middle of the spectrum and may gain some brightness from the parts on either side of it, whereas red is at the end. The normal brightness of red in some red anomalous subjects is most important.

Finally, it is worth giving an example of misuse of the Ishihara Test. A woman was given an official examination with this test and reported " colour anomalous ". The writer was informed by a friend, travelled to her home and tested the woman and her relatives with the Ishihara, Stilling and colorimeter tests. All were quite normal. On enquiry in appropriate quarters it was found that the official Ishihara testing was done with the test on a bench in direct sunlight.

Chapter 8

MATCHING INTERMEDIATE COLOURS

THE aim of this experiment was to measure colour sensitivities in such a way that the colours used to desaturate each other in the colorimeter should be neighbours and not opposites. The primary object of doing this was to meet the possible objection that the use of opposites in the colorimeter to desaturate each other might create artificially the negative correlations between red and green or yellow and blue. If the negative correlations between colours measured as pairs were not found when the pairs were neighbours rather than opposites, then they could be regarded as properties of the colour sensitivities and not as products of the tests. A secondary object was to study in more detail the frequently found tendency to confuse blue-green with green. It was also hoped that the experiment would reveal further characteristics of colour vision not found in the forms of test so far used.

TECHNIQUE

The colorimeter or anomaloscope was used again in essentially the same way as before. There were four sub-tests. The first was a test of red and yellow, the second of yellow and green, the third of green and blue and the fourth of blue and red. The Ilford Spectrum Red, Yellow, Green and Blue colour filters were used for these tests. The red-yellow test was set up with the red filter below and the yellow above it in the right-hand slide. Hence the variable spot was saturated red at a slide reading of zero and saturated yellow at 35·0 mm. The standard spot was made with the Ilford Spectrum Orange filter, and the mixture of red and yellow matched the orange standard at a scale reading of about 19·0 mm. There was little or no change of brightness between red, orange and yellow for the majority of subjects. The 2·02 density neutral filter was placed in the left slide below the orange filter and the orange was slightly diluted with this at a scale reading of 30·0 mm. The brightness of the left-hand standard spot was maintained at a shutter reading of about 12·0 mm., while the right-hand shutter was fully open. This test was easy to carry out efficiently. Testing was begun at a point at which the

variable appeared redder than the orange standard, and continued until it was yellower and back until it was again redder as often as necessary.

The yellow-green test was similarly arranged, using the yellow and green filters, yellow below and green above, to make the variable and the yellow-green filter in place of orange to make the standard. Relative brightnesses were different, and the standard shutter now had to be placed at about 20·0 mm. while the variable again remained fully open. The mixture of yellow and green usually matched the pure yellow-green at a scale reading of about 18·0 mm. This test was carried out from " variable yellower " to " variable greener " and back again. It was an efficient and easy test.

The green-blue test was set up in a similar manner, using the blue filter in place of the green and the green in place of the yellow, on the variable side, and the pure blue-green filter in place of the yellow-green one on the left or standard side. The standard blue-green was diluted with slightly less white light than the yellow-green and orange filters, reading 31·0 instead of 30·0 mm. The blue-green mixture matched the pure blue-green at about 22·0 mm. Brightness was controlled with the variable shutter while the left or standard shutter remained open. It was best to start with the variable bluer than the standard and to proceed towards the greener side and back again. The brightness for the blue side was much lower and the shutter was closed step by step from about 15·0 mm. to 8·0 or 10·0 mm. as the test proceeded, to be opened again in returning to the blue side. This test was more difficult and the subject often uncertain of his judgments; but delay and repetition led to fatigue and greater uncertainty, and in difficult cases it was necessary to have rest pauses between the ascending or descending series of observations. The reasons for the difficulty were: (a) great variation in brightness levels of the blue and green end points, (b) great individual differences in sensitivity to the colour differences being tested, and this was coupled with (c) the ever-present tendency to confuse greater blueness with greater darkness and greater greenness with greater brightness. Steps of two mm. were often needed instead of the one millimetre steps generally used, and the subject was always encouraged to insist firmly on any differences which he suspected. In this way it was ensured that he did not fear that the experimenter was deceiving him. Four and even five millimetre steps were exploited in some cases to give the subject confidence, and brightness matches were always insisted upon before colour equality was accepted.

The blue-red test was set up with blue below and red above in

the right-hand slide, and the spectrum violet in the left slide, set at 20·0 mm., so that the violet standard was desaturated with a considerable proportion of neutral light, because the loss of saturation of the red-blue mixture was great as compared with the red or blue taken alone. The right shutter was now always open and brightness was controlled with the left, which was usually at 20·0 mm. There was little brightness change in doing this test, the colour changes were clear and the subjects were quite confident. The only technical difficulty was that the red-blue mixture, being made up of lights from opposite ends of the spectrum, was inclined to flutter from one colour to the other with some subjects, especially if they delayed or hesitated. The red-blue mixture matched the violet at about 15·0 mm. scale reading.

In all these four tests the source of light was the same 100-watt daylight blue lamp. A change in the lamp would have changed the matching points and spoiled the experiment.

SUBJECTS

The " Intermediates " experiment was carried out on 41 men and 31 women. Of the men 32 had normal colour vision, in the sense that they passed the Ishihara Test, and the remaining 9 were red-green defectives. Six of these were invited as known defectives and 3 were found by chance. The men invited were 2 extreme deuteranopes, 2 green and 2 red anomalous subjects. The 3 abnormal men found by chance were 1 moderate deuteranope, 1 green anomalous subject and 1 extreme protanope. Of the 31 women 30 were normal and 1 was a green anomalous girl found in the random sample.

MID-POINTS

Tables 76—79 show the distributions of mid-points for all subjects in this experiment except the five men who were invited as red-green defectives. The deviations are shown as nearly as possible in multiples of the standard deviation. This classification is not perfect, because the standard deviation and mean were calculated in millimetres to two places of decimals, while the actual figures of the records were always tabulated in single millimetre steps. It is to be noted that these tables include the results for two green anomalous and two red-green blind subjects, whose positions will be discussed at appropriate places. Diagram XXII shows the normal results together with those of five typical red-green defectives.

The data in Table 76 show the distribution of mid-points for the red-yellow test, in which the standard was orange. It will be seen that this distribution is well within the limits of the normal

TABLE 76

MID-POINTS IN THE RED-YELLOW TEST: MEN AND WOMEN

	RED WEAKNESS:		NORMAL:	YELLOW WEAKNESS:			
	−2 to −3 × sigma 16–16·5 mm.	−1 to −2 × sigma 17–17·5 mm.	±1 × sigma 18–20 mm.	+1 to +2 × sigma 20·5–21 mm.	+2 to +3 ×sigma 21·5–22 mm.	Over 3 × sigma Over 22·5 mm.	Totals
MEN	0	7	24	3	0	1	35
WOMEN	0	2	22	5	1	1	31
TOTAL	0	9	46	8	1	2	66

curve with the exception of two subjects who have a large yellow deviation. The most extreme subject apart from these was a girl who was seen before the general results of the test became apparent. Since it was not then realised that she was an exception she was given
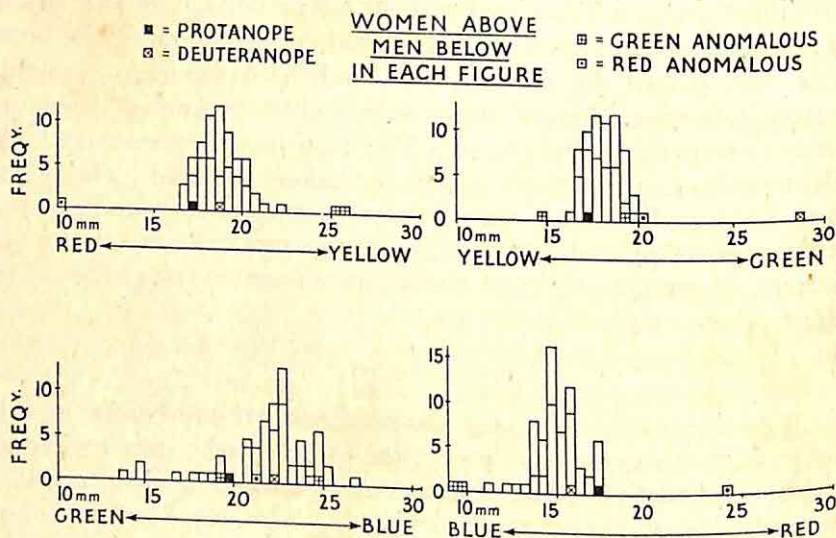
Diagram XXII. Matching Intermediate Colours: Mid-Points: 67 Subjects; Half-Millimetre Steps

no other colour tests at the time and unfortunately lost touch with the experimenter. She did not know of any colour-blind relatives. She shows in a marked form the quality which is characteristic of the green anomalous in these tests, namely, an exceptional range of

matching in yellow and green, while her deviation appears in the
red-yellow test. Her yellow-green range was three times the modal
range in that test, and she would therefore rank as very yellow-green
weak. The two most extreme subjects in Table 76 were the green
anomalous man and woman, who will be discussed more fully in the
section on individual subjects. The two red-green blind men showed
no marked abnormality in mid-points, though, of course, they had
enormous ranges, which will be discussed later.

Table 77 shows the deviations of mid-points for the yellow-green
test. Again the results are well within the normal curve, with very

TABLE 77

MID-POINTS IN THE YELLOW-GREEN TEST : MEN AND WOMEN

	YELLOW WEAKNESS :			NORM.:	GREEN WEAKNESS :			
	Below −3 × sigma. 15 mm. and less	−2 to −3 × sigma 15·5-16 mm.	−1 to −2 × sigma 16·5-17 mm.	±1 × sigma 17·5-19·5 mm.	+1 to+2 × sigma 20-20·5 mm.	+2 to +3 × sigma 21-21·5 mm.	Over 3 × sigma 22mm. and more	Totals
MEN	0	0	5	28	1	0	1	35
WOMEN	0	0	4	25	2	0	0	31
TOTAL	0	0	0	53	3	0	1	66

few exceptions. The exceptions are the moderate deuteranope and
the green anomalous man; the green anomalous woman does not
show a marked deviation in this test. The deuteranope has a very
big deviation, about 10 × sigma, in this test, but a big range in the
red-yellow test.

In the blue-green test, the results of which are shown in Table 78,
there are no subjects outside the normal curve. The three most

TABLE 78

MID-POINTS IN THE GREEN-BLUE TEST : MEN AND WOMEN

	GREEN WEAKNESS :		NORMAL :	BLUE WEAKNESS :		
	−2 to −3 × sigma 13·5 to 16 mm.	−1 to −2 × sigma 16·5 to 19 mm.	±1 × sigma 19·5 to 24·5 mm.	+1 to +2 × sigma 25 to 27·5 mm.	+2 to +3 × sigma 28 to 30·5 mm.	Totals
MEN	2	2	29	2	0	35
WOMEN	1	2	21	7	0	31
TOTAL	3	4	50	9	0	66

extreme are all weak on the green side : two men and one woman. The men both have very marked matching ranges as well as green deviations. Similarly the extreme woman subject in this table is also distinguished more by blue-green weakness than by deviation. None of the colour blind or anomalous subjects had an unusual deviation in this test.

Table 79 shows the deviations of mid-points for the blue-red test. The two subjects who have extreme blue deviations in this

TABLE 79

MID-POINTS IN THE BLUE-RED TEST : MEN AND WOMEN

	BLUE WEAKNESS :			NORMAL:	RED WEAKNESS :		
	Beyond 3 × *sigma*	−3 *to* −2 × *sigma*	−2 *to* −1 × *sigma*	± 1 × *sigma*	+1 *to* +2 × *sigma*	+2 *to* +3 × *sigma*	*Totals*
	11mm. *and less*	11·5- 12·5mm.	13-13·5 mm.	14-16 mm.	16·5-17 mm.	17·5 18·5mm.	
MEN	1	2	0	26	2	4	35
WOMEN	1	0	2	23	3	2	31
TOTAL	2	2	2	49	5	6	66

test were the green anomalous man and woman. The fact that red is stronger than blue for them, just as it is stronger than green or yellow, is evidence that the green anomalous condition in the Rayleigh Equation is due not only to a weakness of green, but also to relatively greater strength of red. This is supported by other facts. Another green anomalous subject invited to do the present tests had precisely the same peculiarity, while one red anomalous subject who was invited had the opposite condition : in him green is stronger and red weaker than in the normal in the ordinary Rayleigh Equation, and red is also weaker than blue in the present test, in which he has a red deviation of more than 3 × sigma.

This is an important point, because it has been said that red or green anomalous colour vision might be due to increase in green or red rather than to decrease in red or green. The present data suggest that it is due to a combination of both tendencies. This may be why it contrasts with other forms or red-green defect, which are distinguished by confusion of colours rather than by deviation in the Rayleigh Equation. It remains unexplained why these anomalous subjects should show a characteristic deviation between red and yellow, but a big range of confusions between yellow and green. The correlations and factorial analysis given later will suggest

that this is a general characteristic of ordinary red and green deviants as well as of the anomalous subjects.

EFFECTS OF BLUE-WEAKNESS

It is interesting to find that the standard deviation of the green-blue test is about twice as great as that of any of the other three. Table 80 shows the standard deviations of these mid-points. The actual mean mid-points have been omitted, because their positions

TABLE 80

SIGMAS OF MEAN MID-POINTS

Test :	R-Y	Y-G	G-B	B-R
Sigma of	1·13	1·10	2·83	1·23
Mid-point	mm.	mm.	mm.	mm.

are dependent on purely physical conditions, and can be tilted to either side at will by increasing the intensity of saturation of one of the colours used. Thus, if a 0·3 density neutral filter is super-imposed upon either filter in any of the tests, it will cut down the intensity of that colour by half, and tilt the mid-points strongly to that side. The standard deviation is not open to this arbitrary control, though many problems about how it is affected by saturation and intensity remain to be settled. Since the differences of the standard deviations of the red-yellow, yellow-green and blue-red tests are about the same as their own standard errors, the subjects are on the whole equally sensitive in these colour comparisons. Since the difference between the standard deviations for the blue-green test and the next larger, that of the blue-red test is more than six times its own standard error, the subjects are on the whole much less sensitive to the green-blue distinction than to any of the other three. This strongly confirms the general impression from everyday life, that the distinctions between near shades of green and blue are more often disputed than any other colour distinctions. It supports the view that these differences are not due to mere differences of naming, but are the result of real differences of colour sensitivity among the persons concerned. The evidence collected from this series and other tests indicates that these differences are most often due to varying sensitivities to blue. Varying sensitivities to green result in differences of opinion about pale greens and yellows, or about pale greens and pinks, while varying sensitivities to blue result in differences of opinion about blues and greens which are desaturated

and about the same brightness. Thus the frequent assertions that Cambridge blue is really a kind of green are due to blue weaknesses. Cambridge blue is a desaturated blue-green, to most people predominantly blueish, but those who have a weakness in blue are less sensitive to the blue in it than the normal, and see it predominantly as greenish. " Eau de Nil " is a similar colour, but predominantly green to the normal, and is therefore less subject to this variation for the blue-weak. " Electric blue ", peacock and even turquoise, are often called " green ".

MATCHING RANGES

The ranges of matching in the intermediates tests are shown in Tables 81—84 and in Diagram XXIII. The range in red and yellow is the double differential threshold for the perception of the
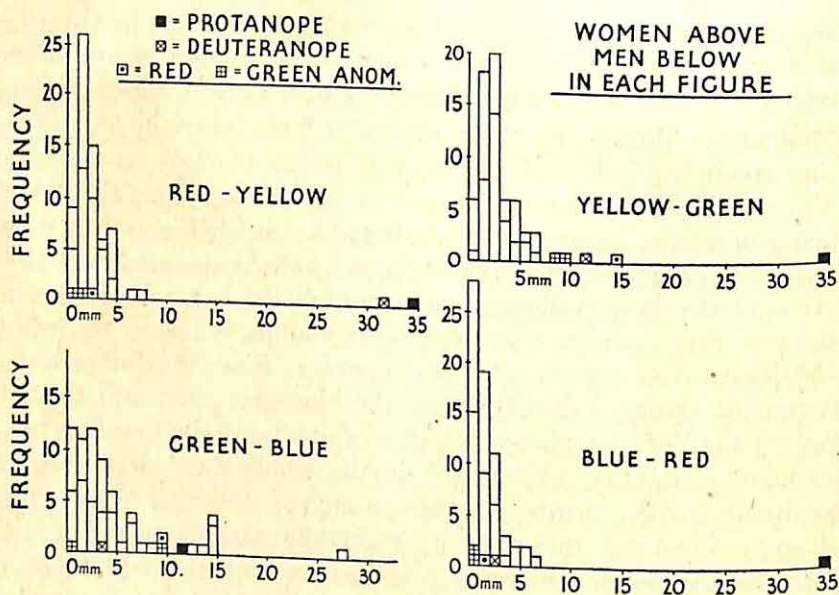
Diagram XXIII.   Matching Intermediate Colours :   Matching Ranges :
67 Subjects : Millimeter Steps

red-yellow mixture as redder or yellower than the orange standard. Similar definitions, with appropriate changes, apply to the yellow-green, green-blue and blue-red ranges. Table 81 shows the matching ranges for the red-yellow test in terms of the modal or most frequent range. All those subjects with more than twice the modal range can be classed as weak in red and/or yellow. The two men, one with

16 times and the other with 18 times the modal range, are both red-green blind, the first being a moderate deuteranope and the second an extreme protanope.

TABLE 81

RED-YELLOW RANGES : MEN AND WOMEN

	1 × mode: 1 & 2mm.	2 × mode: 3 & 4mm.	3 × mode: 6 & 7mm.	4 × mode: 8 & 9mm.	16 × mode: 31 & 32 mm.	18 × mode: 35 & 36 mm.	Totals
MEN	17	14	2	0	1	1	35
WOMEN	18	6	5	2	0	0	31
TOTAL	35	20	7	2	1	1	66

In Table 82 the ranges for the yellow-green test are shown. The subject who had 16 × the modal range is the extreme protanope. Two men had 3 and 4 times the modal range. Of these one had no

TABLE 82

YELLOW-GREEN RANGES : MEN AND WOMEN

	1 × mode 0–3mm.	2 × mode 4–6mm.	3 × mode 7–9mm.	4 × mode 10–12mm.	16 × mode 35mm.	Totals
MEN	24	8	1	1	1	35
WOMEN	20	7	3	1	0	31
TOTAL	44	15	4	2	1	66

other peculiarities, and the other was green anomalous. As mentioned before, like other green anomalous subjects, he showed the peculiarity of a large deviation in the red-yellow test and a large range in the yellow-green test. One of the women who had 4 times the mode is also green anomalous.

Table 83 shows the ranges of matching for the green-blue test. As many as forty-five subjects have twice or more than twice the

TABLE 83

MATCHING RANGES FOR THE GREEN-BLUE TEST : MEN AND WOMEN

	1 × mode: 0–2 mm.	2 × mode: 3–4 mm.	3 × mode: 5–6 mm.	4 × mode: 7–8 mm.	5 × mode: 9–10 mm.	6 × mode: 11–12 mm.	7 × mode: 13–14 mm.	8 × mode: 15–16 mm.	14 × mode: 27–28 mm.	Totals
MEN	13	9	5	3	0	1	1	3	0	35
WOMEN	10	12	3	2	2	0	0	1	1	31
TOTAL	23	21	8	5	2	1	1	4	1	66

1*

modal range, and twenty-one have more than twice this range. If, according to the definition used elsewhere in this book, those with more than twice the modal range can be considered colour weak, about one third of all the subjects would be weak in blue and/or green, although the modal range itself is not greater than that for red and yellow. This accords with the fact already mentioned that near shades of blue and green and of intermediate greenish blues are more often confused than any other hues in daily life.

The most extreme subject in this table, who showed very marked weaknesses in both the tests involving blue, had 14 times the modal range in the blue-green test, and altogether failed to distinguish green from blue-green. She had a range of 7 times the mode in the blue-red test. In the Ishihara Test she could read the figures easily which are supposed to be read only by the red-green blind. She made two errors of an insignificant character in the blue-green plates of Stilling's tables. She knew of her defect, having called a coat " blue " when other people called it " green ". It was in fact a blue-green colour. She said that her father had the same difficulty with blue-greens. Another subject was at the time of this test very reluctant to admit her defect, though she knew perfectly well that it existed, and when doing the beads test she defended her confusion of blue-green with blue by claiming that it was purely a matter of naming. If it had been purely a question of naming, however, she would have been able to distinguish the shades of blue-green and blue to which she applied the name " blue ", just as a person may use the name " brown " for a reddish brown and also for a yellowish-brown, but has no difficulty in sub-dividing brown into two classes according to their reddish or yellowish quality.

Five men and one woman had 7 or 8 times the modal range. Two of the men had no other peculiarity, the third was an extreme protanope and the fourth had in addition rather a large range in red and yellow. He had passed the Admiralty tests for colour without difficulty, but noticed a tendency to confuse blue and green. He had " a difficulty in deciding which is more blueish or more greenish of such colours as electric-blue ". He was given the yellow-blue test described in Chapter VI, and had a large range, 8 mm., with a very big blue deviation, showing marked weakness in blue. The fifth blue-green weak man, a Jew of Dutch descent, had ranges which decrease towards the red-yellow test, thus : B—G, 14 mm.; Y—G, 6 mm.; R—B, 5 mm.; R—Y, 3 mm. Unfortunately it was impossible to detain him long enough to do additional tests. One woman had a range of 15 mm., and no other peculiarity. Her mother's

brother's son is colour blind, having been rejected by the Air Force, but it is reported at home that his greatest difficulty is in distinguishing yellow and white, which is characteristic of people with an extreme yellow weakness rather than of the red-green blind. Her ideas about colours sometimes differ from those of other people, for she calls turquoise blue a kind of green. Two other subjects who have noticed a difficulty with blues and greens may be mentioned. One has a general colour weakness which includes blue, and the other has five times the modal range in the blue-green test, but is not weak in green.

The ranges of matching in red and blue are shown in Table 84. This, like the blue-green test, shows rather a wide spread of ranges,

TABLE 84

RED-BLUE RANGES: MEN AND WOMEN

	1 × mode: 1mm.	2 × mode: 2mm.	3 × mode: 3mm.	4 × mode: 4mm.	5 × mode: 5mm.	6 × mode: 6mm.	7 × mode: 7mm.	35 × mode: 35mm.	Totals
MEN	15	8	6	1	2	2	0	1	35
WOMEN	13	10	5	2	0	0	1	0	31
TOTAL	28	18	11	3	2	2	1	1	66

though the modal range is very small, and 20 subjects out of 66 have more than twice the modal range. The weakest subject is an extreme protanope, and he was unable to distinguish red from blue— equally dark for him. This explains the confusion of red and blue sometimes reported by the colour blind. The woman who has seven times the modal range has already been discussed, and so has the man who has six times the modal range. They were colour weak in blue. The two men who have five times the modal range have their chief weaknesses in blue and green.

It is clear that matching ranges in these tests support the general conclusion from mid-points, that the distinction between blue and green is the most variable of the four distinctions tested, and that red and blue is next to it in variability. This is not altogether consistent with the results of some other tests. In the spectrometer yellow is the most variable in position. In the beads test weakness in yellow leads to confusion of orange with red and yellow with white, while weakness in blue lead to confusions of blue with green and blue-green. Confusions of red and green with yellow are found in the red-green blind, who also confuse violet and purple with blue. Since they are

much less frequent in the population, their errors, though striking, are less often met with than those of the blue and/or yellow weak. Indeed, it is the very frequency of errors due to blue defects that makes us unwilling to accept colour weakness as the explanation. We are inclined to think of these errors as due to differences of naming habits or merely of " opinion ". There is another point, which is clear from all the experiments, namely, that red-green blindness and anomalous colour vision are discontinuous variations, not linked up with the normal curve of colour weaknesses by intermediates, whereas all blue-yellow defects can be included in a normal curve of continuous variations of sensitivity. It is important that the present experiment, in which no colour was measured against its complementary, should support this conclusion, because it shows that the results obtained from the Rayleigh Equation and pairs of opposites and complementaries were not created by the technique of measurement.

SEX DIFFERENCES

It is well known that there are more colour blind and anomalous men than women in the population, and this difference is due to the sex-linked inheritance of red-green defects, which is easily shown by genealogies. Apart from these sex differences it is often held that men are inferior to women as judges of colour, and some researches, such as those of Collins[1] and Houstoun,[2] seem to support such a theory.

In order to test this hypothesis the results of the present experiment were dealt with as follows. Anomalous and red-green blind subjects were first excluded, because they belong to the special sex-linked group. For the remainder, quantities representing sensitivity to each of the colours tested were calculated in the same way as before. In the red and yellow test, for instance, the colorimeter readings for the points at which each subject just failed to distinguish red from the standard orange were tabulated. These were measured from the zero of the scale. Similar quantities were calculated for the distinction of yellow from the orange standard, using the upper limit of the scale as an arbitrary zero, as if 35 mm. scale reading were 0. In the same way all eight series of readings were tabulated, each colour being measured twice, red first in the red-yellow and later in the blue-red test, and so on. Now the differences between the means of the readings for men and for women in all eight sets of measurements were calculated and compared with their own standard errors. Table 85 shows these averages. " Rb " means

red measured in the blue-red test ; " Ry " means red measured in the red-yellow test, and so on throughout the table. All the differences between the means for men and women are about as small as their own standard errors, and no sex differences are revealed at all.

TABLE 85

MEAN READINGS FOR COLOUR SENSITIVITY IN MILLIMETRES: 32 MEN AND 30 WOMEN

	Rb	Ry	Yr	Yg	Gy	Gb	Bg	Br
MEN	18·50	17·75	14·88	16·44	15·34	19·64	10·50	14·69
WOMEN	18·66	17·28	14·40	17·24	14·97	19·98	10·35	14·10

Since we have in these groups of subjects a considerable number, namely about one third, who must be classed as blue-green weak, and since it appears that this peculiarity is an expression of blue rather than of green defect, it may be inferred with some confidence that blue weaknesses are not sex-linked. The results bear equally decisively on yellow weaknesses, and it is a fair inference that there is no sex linkage in the inheritance of either blue or yellow defects. On the other hand, an examination of the frequencies of red-yellow and yellow-green ranges shown in Table 81 and 82 suggests that women have twice the modal ranges more often than men. This would accord with the sex-linked nature of red-green defects, for the excess of women was probably due to the presence of heterozygotes for red-green blindness. Further studies of these problems will have to be made. The pooled frequencies of the red-yellow and yellow-green tests show a larger proportion of colour-weak women than of men, and the probability of that difference being found by chance is 0·03 to 0·02 when tested by the Chi-squared technique with Yates's correction. This is not convincing evidence, but is a strong indication of an excess of colour-weak women in those tests.

HAIR AND SKIN COLORATION

As explained elsewhere it has been suggested that those with more pigmentation are less colour sensitive, and this would fall into line with the hypothesis often put forward, that weakness in colour, particularly in blue or red, might be due to retinal pigmentation. Popular belief, as indicated by frequent questions from subjects doing the experiments, however, is rather in the direction that fair skinned and fair haired people might be less sensitive than the normal.

In order to test these hypotheses each subject was classified as "dark" or "fair" at the time of doing the tests. All those with black or dark hair and/or dark skin were classed as "dark", and the remainder as "fair". It is admitted, as mentioned before, that some were difficult to classify, and a three-fold grouping might have been better. Nevertheless, any tendency for weakness of colour vision to be linked with pigmentation would be apparent in the results, even with a two-fold grouping, and the reduction in actual frequencies in each class would make inferences from the three-fold grouping less easy to draw. Table 86 shows the means for the set of colour sensitivity

TABLE 86

MEAN READINGS FOR COLOUR SENSITIVITY IN MILLIMETRES : 25 "DARK" SUBJECTS AND 37 "FAIR"

	Rb	Ry	Yr	Yg	Gy	Gb	Bg	Br
Dark	18·46	17·62	14·66	16·82	15·34	19·25	10·54	14·38
Fair	18·82	17·59	14·75	16·88	14·97	20·78	10·99	13·99

measurements for the "dark" and "fair" groups : there are no statistically significant differences between the pairs of means, all of which are about the same as their own standard errors. The experiment therefore shows no tendency for hair or skin pigmentation to be linked with variations of colour sensitivity among these subjects.

The ten anomalous and colour-blind subjects were also classed as dark or fair, and this grouping was compared with the frequencies of dark and fair in the whole group. Table 87 shows this comparison.

TABLE 87

COMPARISON OF FREQUENCIES OF "DARK" AND "FAIR" : RED-GREEN DEFECTIVES AND NORMAL SUBJECTS

	Dark	Fair
Red-Green Blind and Anomalous	3	7
Normal	25	37

In this table, Yates's correction being applied because the expected frequencies are small in the red-green defective groups, the Chi-squared technique shows no significant difference between the proportions of dark and fair among "normal" and among red-green defectives. Even if Yates's correction had not been used there would be no significant difference. Considering the great magnitude of the defects of the red-green defectives in comparison with the

variations of the normal subjects, we should expect any tendency for pigmentation to be associated with the defects to be brought out very clearly, but there is none. The colour blind are just as frequently dark (or fair) as other people.

INTER-CORRELATIONS BETWEEN COLOUR SENSITIVITIES AND BRIGHTNESS LEVELS

Using the measurements of colour sensitivity described in the two previous sections, intercorrelations were calculated. Each colour was tested in two different ways and appeared twice in the correlation table. These intercorrelations are on the same principle as those worked out between " colour weaknesses " for the rotating disks and other tests. Correlations were also worked out for each colour sensitivity and the appropriate brightness level, which, for a given colour, is the shutter reading at which the mixture matches the standard for brightness when set at the mean mid-matching point for the whole group of subjects. In the red-yellow and blue-red tests brightness level was controlled by the left shutter, but in the yellow-green and green-blue tests it was controlled by the right shutter. Allowance was made for this difference in calculating the correlations, and in all eight brightness correlations a positive sign meant that an increase of brightness was correlated with an increase of colour sensitivity and a negative sign meant the reverse. Since all the measurements were made on mixtures of colours, both members of each pair being potential variables in brightness, partial correlations were necessitated, the effect of the unwanted colour being thus eliminated.

One subject had a very large weakness in blue, and it seemed possible that her results might introduce error into the correlations, especially because her reading for blue, measured as a pair with green, was far outside the normal curve. Hence she was excluded the second time the correlations were calculated, and it was not until this was done that the resulting factorial analysis became intelligible. The colour blind and anomalous subjects were also excluded, for the same reason.

FACTORIAL ANALYSIS

Table 88 shows the factor loadings for the colour sensitivities measured in the Intermediates Tests, together with brightness level loadings, which were grafted upon the other factor loadings. As before, the symbol " Ry " means red measured in the red-yellow test,

" Rb " means red measured in the blue-red test, and so on for all the others.

It will be seen that there is a small negative loading for " Yr ", yellow measured in the red-yellow test, in the general factor, and the highest positive loadings in this factor are for " Ry ", and " Yg " and " Br ", in that order. Thus it may be inferred that the distinction

TABLE 88

FACTOR LOADINGS FOR COLOUR SENSITIVITIES IN THE INTERMEDIATES
TESTS : 61 NORMAL SUBJECTS : BRIGHTNESS LOADINGS GRAFTED

Colour Tested :	Factor Loadings :		
	I	II	III
Ry	+·531	+·349	−·323
Yr	−·126	−·468	+·285
Yg	+·467	−·153	−·143
Gy	+·233	+·110	+·343
Gb	+·187	+·562	−·593
Bg	+·316	−·406	+·422
Br	+·454	−·623	−·006
Rb	+·015	+·629	+·005
Brightness	+·403	−·005	−·075

of yellow from orange tends to be a special disability, while the most outstanding abilities are the distinctions between red and orange, yellow and green, and blue and violet. We may express this by saying that the ability to distinguish red from orange is the best measure of the kind of sensitivity being measured by this factor, probably brightness, but the ability to distinguish yellow from orange varies in exactly the opposite way and is a test measuring the lack of this factor on the average.

The first bipolar factor groups red and green tests on one side and contrasts them with yellow and blue tests on the other. This contrast would be extremely difficult to reconcile with a three-colour theory, according to which we should expect red, yellow and green to be contrasted against blue, because all variations of red and green sensitivity would, on such a theory, correlate positively with variations of yellow. On a four-colour theory, such as that of Hering, or his theory as modified by Houstoun, however, it would be likely that different psycho-physical functions would be separated by the factorial analysis. In measuring red sensitivity against an orange standard or green against a yellow-green standard, the red-green system would

be contrasted against the yellow-blue system.   Similarly, these systems would be contrasted again in measuring red against a violet standard and green against a blue-green standard, and again in measuring yellow against an orange or yellow-green, and blue against a blue-green or against a violet standard.   On a four-colour theory, therefore, the principal contrasts would be between the red-green and the yellow-blue systems in this experiment, and not between colour sensitivities taken separately, or in any other combination. This expectation is fully supported by the first bipolar factor.

The second bipolar factor, which, with small residuals and no more than sixty-one pairs of measurements correlated, is not decidedly significant, contrasts colours measured as pairs in the tests : " Ry " against " Yr "; " Yg " against " Gy "; " Gb " against " Bg "; and " Br " against " Rb ". This is most important, because it shows the effect of the experimental technique in emphasising contrasts between the colours mixed in the colorimeter. This factor therefore supports the criticism that pairs of colours measured together as mixtures tend to be negatively correlated. It shows that to some extent the negative correlations in the nine-colour experiment may have been produced artificially by the method of desaturating each colour with its opposite or complementary, just as they were produced in this experiment by desaturating each colour with its neighbour. At the same time, this second bipolar factor is barely significant in the statistical sense, and is in any case relatively unimportant because it is the third factor, while the important first bipolar, which is statistically significant, contrasts red-green against yellow-blue vision. Hence the "Intermediates experiment", although it does show that the criticism mentioned has some weight, also shows that its weight is very small and that the other experiments were sound in their support of a four-colour rather than of a three-colour theory.

The grafting of brightness level loadings on the table of factors is interesting. It shows that variations in brightness level are positively correlated with the general factor, which is probably to be viewed as an estimate of brightness sensitivity, but are negatively related to both bipolar factors. The negative loading for the first bipolar factor is negligible. That for the second bipolar is very small. Brightness changes bear little or no relation to variations of colour sensitivity, though they are closely related to the subject's general ability to make colour discriminations. This accords with the results of other experiments. Brightness level is always positively correlated with the general factor, and tends to be correlated with the blue side of the blue-yellow and with the green side of the red-green factors.

The positive correlation with the general factor remains in the present experiment, while the differential correlations with the positive and negative sides of the other factors disappear, as would be expected in an experiment which throws the red-green and yellow-blue functions into contrast instead of separating them.

On Ladd-Franklin's theory, variations in sensitivity to red or green cannot be opposed to variations in sensitivity to yellow. There must be either a positive relationship, since reduction in yellow sensitivity might diminish both red and green, or no relationship at all, since reduction in red or green might not on her theory have any effect on yellow. It is clear that in this experiment we are dealing with an opposition between the red-green and the yellow-blue systems, modified to a small extent by the tendency for colours desaturated with each other to be negatively related. The experiment was designed to differentiate the three- and four-colour theories, and to show which was more likely, and it achieves both these ends, clearly supporting a four-colour theory.

Red-Green Defectives

Ten major red-green defectives took part in this experiment. Table 89 shows their characteristics. It will be seen that three major defective men were found by chance in a sample of thirty-five. This accords well with the proportion of colour-blind subjects reported by many workers using the Ishihara Test, and all these subjects would fail completely on that test. They include a moderate deuteranope, an extreme protanope and a green anomalous man, which is a distribution of types according to expectation, considering the smallness of the sample. It is interesting that one green anomalous subject was found in the thirty-one women. The frequency of women major defectives is, of course, much less than $1/31$, and it was simply a matter of chance that one happened to be included in this group.

Table 89

Major Defectives in the Intermediates Experiment

Men:
- Invited:
  - Extreme Deuteranopes—2
  - Green Anomalous—2
  - Red Anomalous—2
- By Chance:
  - Green Anomalous—1
  - Moderate Deuteranope—1
  - Extreme Protanope—1

Women: By Chance: Green Anomalous—1

The five major defective men who were invited had all been tested in other experiments, and the main interest of asking them to do the present tests was to compare the results with those of the other tests they had done.

The degree of darkening of the red end of the spectrum for the protanope is shown in Table 90, where it is compared with the corresponding brightness levels of the red and yellow mixtures at five millimetre steps of the colorimeter slide for an extreme deuteranope and the average of the normal subjects. Thus the deuteranope

TABLE 90

BRIGHTNESS LEVELS FOR RED, RED-GREEN MIXTURES AND GREEN, FOR AN EXTREME PROTANOPE, AN EXTREME DEUTERANOPE AND AVERAGE NORMAL

		RED		ORANGE				YELLOW	
Slide Reading in Millimetres :		0	5	10	15	20	25	30	35
Shutter reading in Millimetres	Protanope	3	5	5	10	10	10	15	15
	Deuteranope	12	12	12	12	12	12	12	12
	Normal	12	12	12	12	12	12	12	12

has the same brightness levels as the normal, and these do not change in passing from red to green through intermediate mixtures, while the protanope shows marked darkening of the red, approximately normal level of brightness for equal mixtures of red and green, and brightening of the green end to a small degree.

A moderate deuteranope regarded himself as being a little colour blind, and said he tended to mistake purple for blue, was " no good at greens " and had been told that he mistook sea green for grey. He said by mistake that a purple coat was blue. He reported no colour-blind relatives. In the Ishihara Test he failed completely and would be classed by it as " totally green-blind ". In the intermediates tests he had a very large range in the red-yellow test, being just able to distinguish the most saturated red from orange, but making no other distinction. In the green-yellow test he had a smaller range, only twice the mode, but a very big deviation to the green side (about 8 × sigma). In this test he called the yellow " red " but failed to distinguish green from the yellow-green standard. His performances on the blue-green and blue-red tests were almost normal. This subject did the red-green Rayleigh Equation as described in Chapter VI, and had a matching range of 15 out of 35 millimetres with no deviation. This being so he could not possibly be classed as green anomalous,

but must be viewed as a moderate deuteranope who has no deviation. It will be valuable to compare him with the truly anomalous subjects now.

Table 91 shows the deviations and ranges for the anomalous subjects in the red-yellow, and yellow-green tests, which are of special interest. It will be seen that the four green anomalous subjects all have large deviations towards yellow in the red-yellow test. These deviations are six or more times the standard deviation (sigma) for normal subjects. In the yellow-green test, however, one red anomalous and two of the green anomalous subjects have a small deviation

TABLE 91

RANGES AND DEVIATIONS OF ANOMALOUS SUBJECTS : RED-YELLOW AND YELLOW-GREEN

SUBJECT :		RED-YELLOW TEST		YELLOW-GREEN TEST	
Sex	Defect	Deviation	Range	Deviation	Range
m	G. Anom.	+8·5mm.	2·0mm.	+2·5mm.	14.0mm.
m	G. Anom.	+7·0mm.	1.0mm.	−3·5mm.	9·0mm.
m	G. Anom.	+7·0mm.	1·0mm.	−3·0mm.	25·0mm.
f	G. Anom.	+6·0mm.	2·0mm.	+1·0mm.	10·0mm.
m	R. Anom.	−9·0mm.	3·0mm.	+1·5mm.	14·0mm.
m	R. Anom.	−7·0mm.	1·0mm.	−3·5mm.	1·0mm.

towards green, while the other three have small deviations towards yellow. These deviations are between one and three times the standard deviation. Both red anomalous subjects have very large deviations towards red in the yellow-red test. Hence we may say that large deviation is characteristic of the anomalous in the red-yellow test, whether it be towards yellow (for the green anomalous) or towards red (for the red anomalous). In the green-yellow test their deviations are small and not regular. On the other hand, matching ranges are small or normal in the red-yellow test, but in the yellow-green test 5/6 are very large. Big ranges are characteristic of the anomalous in this test and big deviations in the red-yellow test. This differentiates them sharply from the red-green blind, whether extreme or moderate, who always have a big range and sometimes a big deviation in both tests. It is striking that neither red anomalous subject is symmetrically opposite to the green anomalous. If they were we should expect them to show a big range in the red-yellow and a big deviation (to the yellow side) in the yellow-green test. The asymmetry of the results corresponds to an earlier finding, for normal subjects, that there tends to be a negative correlation between red and yellow

measured against the orange standard. Negative correlations are produced by deviations without range; ranges with variable deviation tend to produce no correlation; and ranges without deviation tend to produce positive correlations. It is remarkable that the first red anomalous subject, for whom the red was darkened, had a large range in the yellow-green test, but the second, for whom it was not darkened, had a normal range on that test.

While we can say that in comparison with the normal the green anomalous subjects all show relatively greater sensitivity to red than to green, the red anomalous appear to show relatively greater sensitivity to green than to red, and both tend to confuse green and yellow but not red and yellow. The difficulty of getting red anomalous subjects has been very great and these results will have to be confirmed on a larger number of individuals, and especially the red anomalous with red of normal brightness.

Thus it would appear that the " Intermediates " tests do not reveal any new characteristics of the colour blind, but they do reveal important new features of the anomalous, and further study of these may be valuable for problems of colour vision.

Chapter 9

THE FOUR-COLOUR TEST

IT was decided to set up the simplest test which would reveal efficiently the most frequent and important defects of colour vision. The nine-colour experiment showed that red, yellow, green, and blue must be tested, and that orange, yellow-green, blue-green, violet and purple could be neglected. If the test of violet and yellow-green had revealed yellow defects efficiently, this might have been better than the test of blue and yellow, because it would reveal the darkening of violet, which is sometimes found. On the other hand, it was clear that no subjects with darkened violet were normal in blue, and, since the measurement of the degree of violet-darkening was not important, whereas efficient testing of yellow might be valuable, it was decided to use the blue-yellow test and to omit from the short battery the yellow-green and violet test. About the red-green test there was no question; it was both satisfactory and essential.

The choice therefore fell upon the red-green and yellow-blue tests. It was noticed, however, that the average mid-points of these tests were rather strongly tilted to the green and yellow sides respectively, while the matching ranges in the yellow-blue test were unduly large, since a number of subjects went right to the yellow end of the scale. Other points to be considered were that the number of filter changes could be reduced by careful planning of the technique, and that it would be better to use an ordinary half-watt lamp with standard daylight filters than the daylight blue lamp. Changes were therefore introduced which will now be described.

Details of the Four-Colour Test

The red-green and yellow-blue sub-tests of the nine-colour experiment were used with a single coil half-watt lamp of 100 watts, the single coil being preferred because it is much less easily damaged by jolts than the coiled-coil. Two Ilford 37/43 half-watt to daylight filters were introduced, one on each side of the colorimeter, between the telescope lens and the opal screen, in the slots provided for additional filters. This gave a more adequately

standardised white light than that of the daylight blue lamps previously used, since the blue of these lamps is rather variable, not only from lamp to lamp, but also from one side of the globe of a single lamp to the other, owing to differing thicknesses of the glass. This brought the average mid-point of change in the red-green test down to about 19 mm. of right-hand slide reading, as desired, so that more scope was now left for measuring green weaknesses. In order to bring the average mid-point of the yellow-blue test to about the same position, the Ilford spectrum violet filter was introduced above the neutral filter on the left side for the yellow-blue test, replacing the yellow filter used in the red-green test. This enabled the standard grey spot of the yellow-blue test to be made faintly more blue than it had been before. The average mid-point of the yellow-blue test could now be tilted towards the blue end of the right-hand scale by adding a little violet to the standard left-hand spot. The most satisfactory position for the violet filter was now determined by experiment on a preliminary group of subjects, so that the average mid-point for the yellow-blue test would be about 19 mm. of right-hand slide scale reading. This was found to be at 20 mm. of scale reading of the left-hand slide. The effect was not to make the spot noticeably blueish, but simply to tilt the average mid-matching point to the required degree to the blue side. Adequate head-room was thus gained for testing yellow-weaknesses.

The arrangement of shutter openings was now adjusted to bring the average brightness of the red-green mixture down to about the same level as that of the yellow-blue mixture at 19 mm. of right-hand slide scale reading for yellow and blue. This was done by putting the red and green filters in the left slide and the yellow and blue filters in the right, red and yellow below and green and blue above. Then the two slides were set at 19 mm., and the left shutter was adjusted until the brightness of the two spots appeared the same to selected subjects. It was realised that this determination applied only to the individuals on whom it was made, but it certainly gave a better arrangement than with no such adjustment. The position for the left shutter was at 20 mm., and throughout the four-colour test the red-green spot was dimmed by setting its shutter at 20 mm., which made it about the same brightness as the yellow-blue spot in its position of average grey mixture.

The set-up for the tests was now as follows :—

(1) Red-Green Test—R. Slide : Red below, Green above; L. Slide : Neutral 1.02 below, Yellow above; Both shutters at 20 mm.; Left slide at 35 mm.; R. Slide as required.

(2) Yellow-Blue Test—R. Slide: Yellow below, Blue above; L. Slide: Neutral 1·02 below, Violet above; R. Shutter open; L. Shutter at 10, 11 or 12 mm. or whatever brightness level required; L. Slide at 20 mm.; R. Slide as required.

This arrangement enabled the neutral filter to be kept always in place, thus saving time in filter changes; it gave almost equal brightness of the spots for both tests, and it enabled the brightness control to be carried out always with the left shutter, and not sometimes with the left and sometimes with the right, as in the nine-colour

L.	R.	L.	R.
YELLOW	GREEN	VIOLET	BLUE
NEUTRAL	RED	NEUTRAL	YELLOW

COLOUR FILTERS
FOR THE
RED-GREEN TEST

COLOUR FILTERS
FOR THE
YELLOW-BLUE TEST
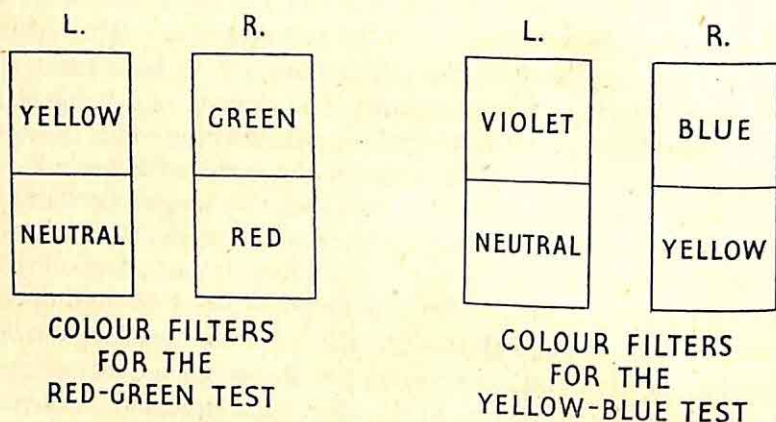
Diagram XXIV. Colour Filters for the Four-Colour Test

experiment. There were two other advantages, namely that all increases in L. shutter readings represented darkening of test colours, and *vice versa*, while all colour sensitivity readings were in standardised directions, i.e., decrease for red or yellow and increase for green or blue. After preliminary trials the new technique appeared satisfactory and systematic testing was started.

A further adjustment was made at this stage. An aluminium disk was cut out, with two sets of holes bored in it. These holes were arranged in pairs, the members of each pair being opposite each other. The disk was fitted in front of the lamp box, with a centre screw, so that it could be turned into any of the five positions. The pairs of holes then formed five different sizes of images on the opal screen: $\frac{3}{4}$ inch diam.; $\frac{1}{2}$ inch diam.; $\frac{3}{8}$ inch diam; $\frac{1}{4}$ inch diam.; $\frac{1}{8}$ inch diam. Then five different sizes of light spots could be used for testing, to imitate signal lights at different distances, as with the familiar Edridge-Green lantern. Such a disk is easily made and fitted, and holes can be bored of sizes to suit any requirements, while there is no difficulty in arranging mirrors so that the test spots can be any

distance from the subject. Alternatively, if one shutter is closed, a single spot can be used for direct colour-naming tests. Thus the colorimeter was made comparable with the usual lantern tests.

INSTRUCTIONS AND TECHNIQUE

Apart from these changes, the method of carrying out the tests was essentially the same as before. The ½ inch diam. holes were used throughout. The red-green filter-pair was set at about 15 mm. slide reading, and the yellow-neutral pair at 35 mm. The room light was switched off, and excessive streaks of light from the apparatus were cut off by adjusting a black cloth, so that the room remained dimly lighted, as in previous experiments. The subject was then instructed as follows : " This is a test of colour vision. Here are two spots of light. This (indicating it) we shall call the right-hand spot, and that (indicating it) the left. I want to find out how good you are at distinguishing these spots by colour (or shade) alone. Are they of the same brightness (or intensity)? (If not, adjust the left-hand spot until the subject is satisfied that they are equal in that respect.) Can you see a colour difference now ? (If so) What is it ? Name the colours of the spots." (If not, then the red-green spot must be turned towards the red end of the scale until the subject does see a difference, unless, of course, he is extremely red-green blind and does not see a difference at all, and then we shall have found out that he is defective.)

Usually the red-green spot would appear redder at 15 mm. with normal subjects, and the test was started with them at this point or any other suitable point at which it appeared redder. In order to catch the subject if he has by any chance been warned, it is an advantage to start sometimes with the spot at a greener position, but the technique is essentially unchanged whichever way the test is started. The experimenter must on no account use any colour names not used by the subject, and must accept any colour names used by the subject, or distinctions made or not made by him, without any hesitation or surprise, and must on no account correct him. If the subject asks a direct question about the correctness of his judgments, the tester must say blandly that he does not know because he cannot see colours himself! This usually makes the subject laugh and lets him realise that no help is being given.

As in previous experiments, the red-green spot is now changed step by step, usually one millimetre at a time, until it becomes equal to the left and then greener (or redder, as the case may be). With certain subjects the left or standard spot becomes redder before

the right becomes greener in appearance. This is taken as the point of change required. The majority find a colour match at about 19 mm. Certain subjects are doubtful and fail to find a point of exact equality. In this case the central position of their readings is taken arbitrarily as one of " equality ", and usually they are among the most normal, and it will be 19 mm., as with the majority. It is necessary to take this step because some hyper-critical subjects make difficulties for the tester by disputing the possibility of equality, and, as indicated before, some defective subjects try to defend themselves against detection by never admitting that two hues are identical. Throughout the test the brightness level of the left spot will be adjusted as required to maintain a continuous equality of brightness between the two spots, and care must be taken to make certain that the subject is not using the term " brightness " as equivalent to " saturation ".

If the technique described is followed resolutely, colour-blind and anomalous subjects will not be missed, but it is as well to do another test because most of them want reassurance that no mistake has been made. As soon as it is realised that a subject is red-green blind, the test must be re-started with the red-green slide at zero, and a rough estimate must be made of his range, probably in 5 mm. steps, or even 10 mm. steps if he is very defective. This estimate may then be narrowed down by systematic testing in small steps at the end points of his matching range, taking each end point separately to avoid fatigue and waste of time. Great care must be taken with all red-green blind subjects to be sure that the brightness matches are unequivocally established before any claims of colour difference are entertained. This is especially important at the red end. If the subject is a protanope the brightness levels *must* be measured accurately, at every step taken. This is always important, but with protanopes it is quite essential, and without it the whole test is simply futile, because they are experts at detecting what other people call differences of hue by noticing brightness differences.

In dealing with anomalous subjects less difficulty will be met with, but the tester must not be misled by his own very different impression of the colours of the spots! Often the green anomalous say " redder " until their point of equality is reached, but beyond it they do not see the standard as " yellower " and the variable as " greener " in the way a normal person would, they tend to see both spots as " green " because spectrum yellow usually looks " green " to them. The critical distinction then is that the variable will look relatively more and the standard less saturated green, as soon as the point of change to " greener " is passed. The reverse condition is found with the red

anomalous, who tend to see the spectrum yellow as " red ". For them the variable spot looks " greener " until the point of equality is reached, then it is " equal ", and after this point it becomes relatively redder than the standard, which is a less saturated red for them. The intending tester will be well advised to experiment with a number of colour-blind and anomalous subjects in order to gain practical experience, provided he is not misled by results obtained on them previously with the Ishihara and other tests, which are often very confusing.

For the yellow-blue test a similar procedure was adopted, starting usually with the variable spot bluer than the standard, with the scale reading at about 25 mm. This generally gave the response " bluer " if a brightness equality had been previously established with the left shutter at about 9 or 10 mm. Then steps were taken until the matching range was established, brightness being subject to readjustment at each step by opening the left shutter as the standard became less blue, equal to and finally more yellow than the variable. Often the yellower hue was called " pink " or even " red ", and often the left spot changed to " bluer " before the right changed to " yellower ". Any named or unnamed colour difference was accepted as " different ", and the names used were recorded as they are often interesting. The steps in this test were usually of 1 mm., but with difficult subjects, or those with marked yellow-blue weaknesses, it was often an advantage to use 2 or even 3 mm. steps, or to map out the matching range in 5 mm. steps as with the red-green blind in the other test. The subjects were always encouraged to do their very best to see any differences and not to fail to point them out to the tester. Certain subjects, however, are specially fatiguable, and a look-out must be kept up for them.

SUBJECTS

The four-colour test was carried out on more than 330 men and 260 women, making a total of over 1,100 subjects tested in all the experiments and tests described in this book. The men tested in the four-colour test, excluding five major defectives tested by Mr. Brown, included 26 protanopes (6 by chance), 39 deuteranopes (8 by chance) 42 green anomalous (11 by chance) and 9 red anomalous subjects (1 by chance.) The women included 3 deuteranopes (all invited), 9 green anomalous (1 by chance) and 1 red anomalous (invited), together with 18 women who were invited because they were known to have colour-blind relatives. Many of the subjects

tested were students in the Psychology Department, and a large number were Medical students.

Throughout, the subjects were tested alternately with the red-green and the yellow-blue tests first, so that any effects due to order of tests were distributed. In general it was found that a quarter of an hour allowed time for testing an individual, inquiry about possible colour-blind relatives and about any difficulties or unusual experiences with colours in daily life, writing up of the test results, and sometimes it allowed time to do the Ishihara Test as well. For colour-blind subjects more time was often needed. Where necessary, a special appointment was made to deal with an unusually interesting subject at leisure, and all major red-green defectives were encouraged to discuss their experiences and possible difficulties and to give their opinions of the tests and of the justice of the conclusions drawn.

DEVIATIONS AND MID-POINTS

Table 92 and Diagram XXV show the frequencies of mid-points (or deviations) in the red-green test, in approximate multiples of the standard deviation, for all except major red-green defectives. It will be seen that the distribution closely approximates to a normal curve and that the difference between men and women is not significant.

TABLE 92
MID-POINTS IN THE RED-GREEN TEST

	Scale Reading in Millimetres																		
	Red Deviation							±1 × sigma				Green Deviation						
	>3 × sigma	−2-3 × sigma		− 1-2 × sigma								+1-2 × sigma			+2-3 × sigma			>3 × sigma	
	14·5	15	15·5	16	16·5	17	17·5	18	18·5	19	19·5	20	20·5	21	21·5	22	22·5	23	Totals
M	1	1	1	6	3	10	9	29	25	43	23	23	4	7	2	3	1	0	191
W	0	0	1	4	3	10	10	30	26	50	26	24	7	10	2	3	1	1	208
TOTALS	1·	1	2	10	6	20	19	59	51	93	49	47	11	17	4	6	2	1	399

The most extreme man subject could not be called red anomalous because he passed the Ishihara Test with only three errors and there was no convincing evidence of a sex-linked red-green defect. Red was slightly darkened for him, however, and his mother had twice the modal range in red and green, though both his sisters were normal. His maternal uncle was reputed to have been red-green blind, but had been dead some years and there was no record of an efficient test on him. The present subject passed the Board of Trade Colour

Vision Tests and went into the Merchant Navy. More efficient investigation is required of cases like this, in order to find out whether the possible evidence of a sex-linked red-green defect can be established beyond doubt.

The most extreme woman subject was unfortunately not given the Ishihara Test, and when she was tested it was not realised that she was just outside the $+ 3 \times$ sigma limit. When this was found, two years later, on analysing the results, she could not be recalled
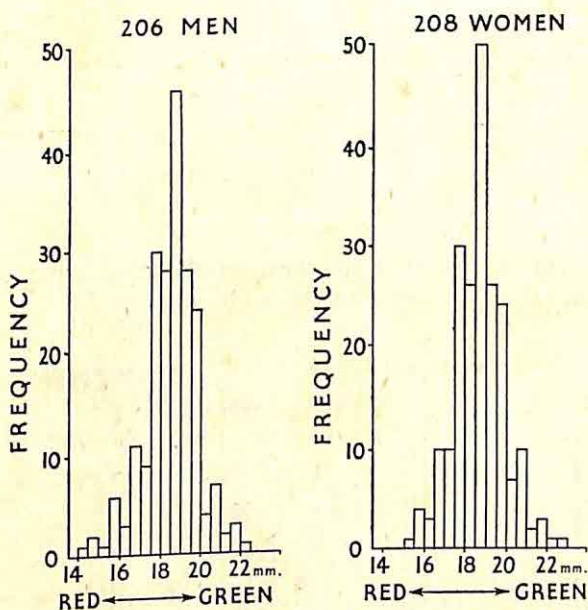
Diagram XXV. Four Colour Test: R-G Mid-Points: Normal Subjects. Half-Millimetre Steps

for additional tests. The other extreme deviants need not be dealt with in detail here. Since there are as many women as men in the groups falling between $+$ and $- 2$—$3 \times$ sigma, it seems evident that such deviations are not sex-linked. We are therefore justified in assuming that none of the extreme deviant subjects could reasonably be classed as red or green anomalous. This is an important point, because, when we do come to deal with the real anomalous subjects a very marked sex difference in frequencies is found.

Table 93 and Diagram XXVI show the yellow-blue deviations grouped as multiples of the standard deviation. It will be seen that there are five men and one woman below the limit of $- 3 \times$ sigma and three women above the limit of $+ 3 \times$ sigma. There is also a significant difference between the distributions for men and women,

which suggests that women are more often blue and men more often yellow deviants, but the difference of the mean mid-points is not significantly greater than zero. A study of the individual extreme

TABLE 93

DISTRIBUTION OF MID-POINTS IN THE YELLOW-BLUE TEST

	SCALE READING IN MILLIMETRES							
	YELLOW DEVIATION				BLUE DEVIATION			
	Below 3 × *sigma* 15 *and less*	− 2-3 × *sigma* 15·5– 16·5	− 1-2 × *sigma* 17–18	± *sigma* 18·5– 20·5	+ 1-2 × *sigma* 21–22	+ 2-3 × *sigma* 22·5– 23·5	*Above* 3 × *sigma* 24 *and above*	*Totals*
M	5	3	26	133	21	3	0	191
W	1	1	11	151	33	8	3	208
TOT.	6	4	37	284	54	11	3	399

deviants in this test would not add anything to what has already been said on that subject in previous chapters.

Diagram XXVI. Four-Colour Test : Y-B Mid-Points : Normal Subjects. Half-Millimetre Steps
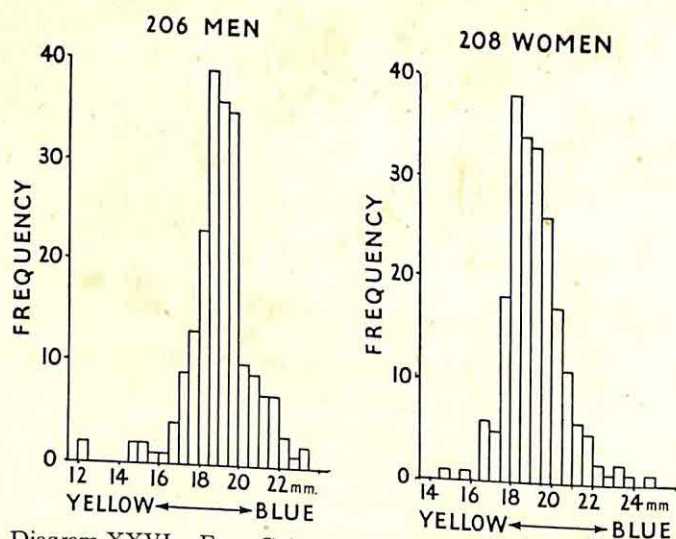
Any person with a deviation of three or more times the standard deviations in either or both of these tests must be regarded as having a small but decided defect in sensitivity to the colour or colours in question. These defects are usually sufficient to have been noticed in daily life by the individuals or their friends, but are not sufficient

to cause failure on any of the colour-vision tests in general use, while they appear to be much less than any form of sex-linked red-green defect (except in heterozygotes). In choosing persons for training in any occupation in which high colour sensitivity was required, however, it would almost certainly be an advantage to exclude all
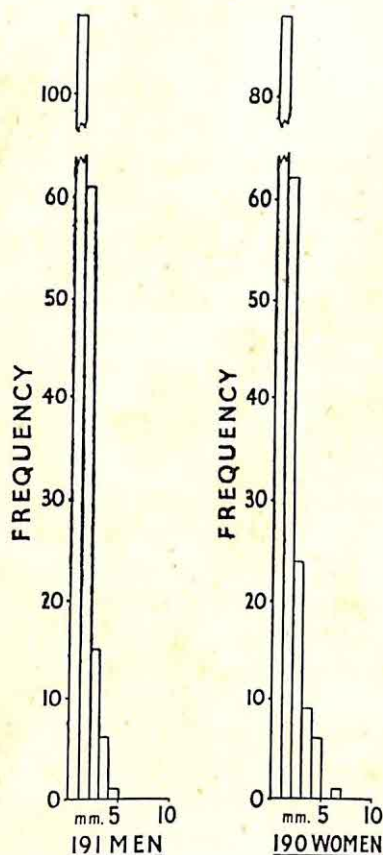
Diagram XXVII. Four-Colour Test : R-G Matching Ranges : Normal Subjects; Millimetre Steps

such subjects. Their deviations are found to be very constant on testing over again with the same tests. To exclude only the red and green deviants would not be sufficient. The yellow and blue deviants must be excluded as well.

MATCHING RANGES

In Table 94 and Diagram XXVII the distributions of red-green matching ranges are shown for men and women separately. Here

the 18 women who were invited because they were known to have red-green blind relatives have been excluded. In the red-green

TABLE 94

RED-GREEN MATCHING. RANGES: MEN AND WOMEN

Range in mm.	1	2	3	4	5	6	7	Totals
MEN	108	61	15	6	1	0	0	191
WOMEN	88	62	24	9	6	0	1	190
TOTAL	196	123	39	15	7	0	1	381

test any person with more than twice the modal matching range must be regarded as red-green weak, whether he has a large deviation or not. If he has a large deviation as well as a large matching range, then his colour weakness is so much the greater. About 11—12% of men and about 20% of women were red-green weak in this test, and this will be discussed in a later paragraph.
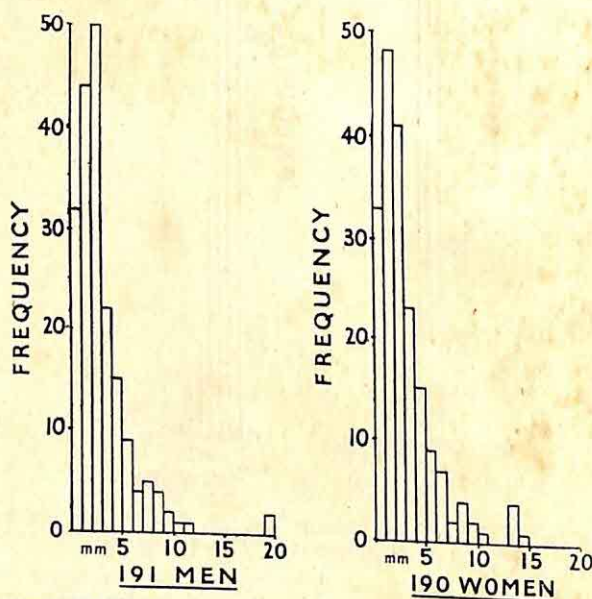
Diagram XXVIII. Four-Colour Test: Y-B Matching Ranges.
Normal Subjects: Millimetre Steps

Table 95 and Diagram XXVIII show the matching ranges for the yellow-blue test. In this test we can take 2—3 mm. range as the mode, and regard any subject with 6 mm. range or more as yellow-blue weak. About 15% of men and women are yellow-blue weak on this criterion, and there is no sex difference. This seems to

correspond well with the findings of other tests, but the actual level to be used as a criterion of colour weakness will have to be settled by further experiments, and must always vary to some extent with the kind of task for which colour sensitivity is being measured. However, in the red-green test it is at about twice the modal range that the frequency of women begins to differ markedly from that

TABLE 95

YELLOW-BLUE MATCHING RANGES : MEN AND WOMEN

Range in mm.	1	2-3	4-5	6-7	8-9	10-15	16-20	Totals
MEN	32	94	37	13	9	4	2	191
WOMEN	33	89	38	16	6	8	0	190
TOTAL	65	183	75	29	15	12	2	381

of men, and, as the women who differ at that level are probably heterozygotes for red-green blindness, there would appear to be a justification for taking this level as a criterion, at least for the red-green test.

A careful study of the subjects with extreme matching ranges in both or either of these tests, shows that their defects are nearly always slightly noticeable in daily life, but do not amount to colour blindness in the sense of causing failure on one of the generally accepted tests, such as Stilling's Tables. The most red-green weak women (excluding the anomalous and colour blind) are probably for the most part heterozygotes for major red-green defects, but their weaknesses are much less than the weaknesses of the homozygous women defectives.

From a practical point of view the exclusion of all subjects who have matching ranges of more than twice the modal range from any training or occupation which calls for fine colour discrimination will be a great advantage, and any subjects who also have large deviations should be excluded all the more firmly.

RED-GREEN BLIND SUBJECTS

There were sixty-eight red-green blind subjects in the series who did the four-colour test, and three of these were women. It has not been possible to include all these subjects in the diagrams. Table 96 shows the frequencies of protanopes, deuteranopes and those who fell into the selected and invited groups. Since six protanopes and eight deuteranopes fell into the random sample of 217 men, there were about 2·8% of protanopes and 3·7% of deuteranopes, making up

6·5% of red-green blind subjects (excluding, of course, all the anomalous subjects). In the use of Holmgren's Wools Test it was often found that there were 3—4% of colour-blind men.[1] The most extreme protanopes and deuteranopes tend to fail on this test, but moderately and slightly red-green blind subjects (excluding the deviants, colour weak and anomalous) tend to pass. The Ishihara Test has increased the proportion of " colour blind " usually found to about 7·8% because it fails all protanopes and deuteranopes and the anomalous subjects as well. The doubtful failures on the

TABLE 96

Red-Green Blind Subjects in the Four-Colour Test

| | INVITED | | CHANCE | | |
	Protanopes	Deuteranopes	Protanopes	Deuteranopes	TOTALS
MEN	20	31	6	8	65
WOMEN	0	3	0	0	3

Ishihara Test are generally either slight deuteranopes, or red-green weak subjects who are probably neither sex-linked defectives nor women heterozygotes. The present test, which is more discriminating, clearly differentiates the anomalous subjects and fails all the red-green blind, and hence it gives the 6·5% of red-green blind subjects mentioned above, excluding the anomalous who will be considered later. Two colour-blind women are included in the series, but fall into the invited group. The proportion of protanopes to deuteranopes is 6 to 8, which suggests that there are more deuteranopes in the population. This is confirmed if we consider those invited as well as those found by chance. The proportion then becomes 26 to 39, and, since there was no selection between the two types in the invitations, this ratio may be taken as an indication of the relative frequencies of the two classes of defectives in the population at large. Deuteranopes are more common.

TABLE 97

Matching Ranges in mm. for Red-Green Blind Subjects in the Four-Colour Test

| | Red-Green Matching Range in mm. | | | | | | | |
	4-5	6-10	11-15	16-20	21-25	26-30	31-35	Totals
PROT.	0	0	2	1	3	5	15	26
DEUT.	3	19	2	4	2	5	4	39
WOMEN DEUT.	1	2	0	0	0	0	0	3
TOTAL	4	21	4	5	5	10	19	68

Table 97 and Diagram XXIX show the matching ranges for these red-green blind subjects, in the red-green test, while Table 98 shows their matching ranges in the yellow-blue test. It is seen that there is a decided tendency for protanopes to be extreme rather than moderate, while deuteranopes are more often moderate than extreme. Evidently the majority of deuteranopes are less defective
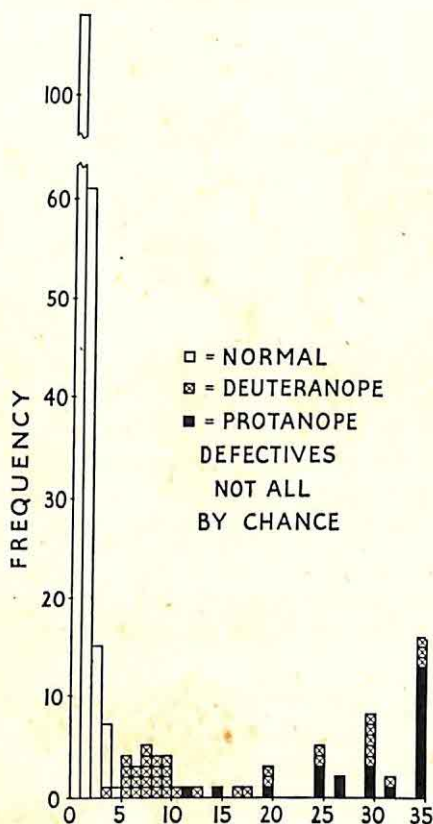
Diagram XXIX. Four-Colour Test: Red-Green Ranges.
191 Normal Men, 25 Protanopes, 38 Deuteranopes;
Millimetre Steps

than any of the protanopes, though some of them are quite as defect-ive as the protanopes who are most extreme. Since there are few who fall into the middle groups of matching ranges, it is convenient to use about 16 mm. as a division between moderate and extreme defectives.

In the yellow-blue test it is seen that the modal matching ranges for protanopes and deuteranopes are not greater than for normal

subjects, and there is no difference between protanopes and deuter-
anopes in this respect. The red-green blind are just as sensitive
to yellow-blue differences as normal people. One deuteranope
showed a very marked weakness in yellow, but was only a moderate
deuteranope, and it is quite certain that extreme yellow defects

TABLE 98

MATCHING RANGES IN YELLOW AND BLUE FOR RED-GREEN BLIND SUBJECTS IN THE FOUR-COLOUR TEST

| | YELLOW-BLUE MATCHING RANGE in mm. | | | | | | | | | |
	1–2	3–4	5–6	7–8	9–10	11–12	13–14	15	20	Totals
PROT.	10	10	3	1	2	0	0	0	0	26
DEUT.	12	14	5	1	4	1	0	1	1	39
WOMEN DEUT.	1	1	1	0	0	0	0	0	0	3
TOTAL	23	23	9	2	6	1	0	1	1	68

do not in general result from extreme defects in red and/or green.
He explained that he had a tendency to confuse yellows and greens,
and said that he once selected a yellow-looking trunk as being his,
when on a Highland pier, after leaving a ship, only to find when he
got home that it was not the right one, when his wife pointed out to
him that it was green.

The distribution of mid-points in the red-green test for the colour-
blind subjects is shown in Table 99 and Diagram XXX. It is seen

TABLE 99

MID-POINTS IN THE RED-GREEN TEST FOR COLOUR-BLIND SUBJECTS

| | RED-GREEN MID-POINTS in mm. | | | | | | | | | |
	6·5	12·5–14	15–16·5	17–18·5	19–20·5	21–22·5	23–24·5	25–26·5	27	Totals
PROT.	1	2	5	17	1	0	0	0	0	26
DEUT.	0	0	2	12	9	0	4	9	3	39
WOMEN DEUT.	0	0	0	0	1	0	1	1	0	3
TOTAL	1	2	7	29	11	0	5	10	3	68

that protanopes are less scattered than deuteranopes, whose distribu-
tion suggests a bi-modal pattern, with peaks at about 19 and about
25 mm. This shows two different hereditary tendencies, a point which
will be dealt with later. One protanope has a very large red deviation,
and he will have special mention in the sequel. All those subjects

with very marked green deviations are deuteranopes, but not all with strong red deviations are protanopes. Hence this table gives more support to the view that protanopes should have red and deuteranopes green deviations, when their mid-matching points are not centrally placed, than other similar tables in earlier chapters. It still shows, however, that the mid-points would be useless as indications of the
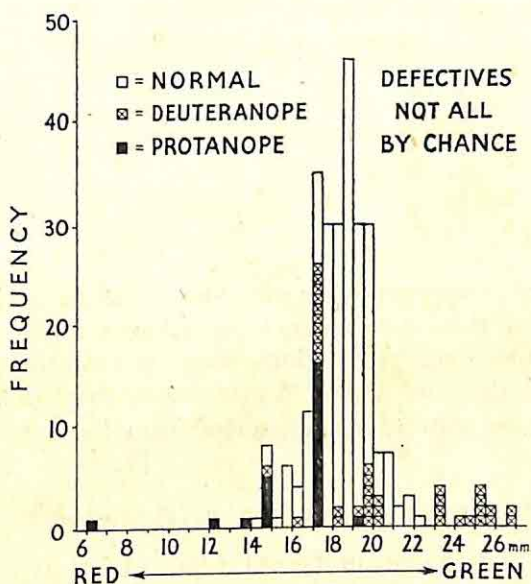
Diagram XXX. Four-Colour Test: Red-Green Mid-Points. 206 Normal Men, 25 Protanopes and 38 Deuteranopes; Half-Millimetre Steps

distinction between protanopes and deuteranopes. It may be remembered that in some of the red anomalous subjects the red end of the spectrum is not dark. It is possible that those deuteranopes who have a marked red deviation might be a special class of defectives. They might in fact be viewed as " protanopes " with red not darkened, if such a condition can be conceived. This would give us a third class of colour blind. There is, however, a decided indication of two kinds of deuteranopes, those with and those without marked green deviation, while some deuteranopes may have darkened green, but no examples of this condition have been met with in the present research. Similarly, there is always the possibility that green anomalous subjects might occasionally have the green darkened, just as there are red anomalous subjects in whom red is of normal brightness. It is an advantage for research that all such possibilities should be kept in mind, though cautiously.

The corresponding distributions of mid-points for the yellow-blue test are shown in Table 100. It will be seen that in this test both protanopes and deuteranopes tend to have normal mid-points,

TABLE 100

MID-POINTS IN THE YELLOW-BLUE TEST FOR RED-GREEN BLIND SUBJECTS

	MID-POINTS IN mm. YELLOW-BLUE							
	12–14.5	15–16.5	17–18.5	19–20.5	21–22.5	23–24.5	25–26.5	Totals
PROT...	0	1	10	12	1	1	1	26
DEUT.	3	0	10	18	5	0	3	39
WOMEN DEUT.	0	0	1	1	1	0	0	3
TOTAL	3	1	21	31	7	1	4	68

though three deuteranopes have exceptional yellow deviations. In the normal group there were 6/399 such yellow deviants, and among deuteranopes there are 3/39, which suggests that there are more yellow extreme deviants among deuteranopes than among normal people, though the number of deuteranopes sampled is too small to be conclusive.

DARKENING OF THE RED IN PROTANOPES

The degree of darkening of the red colour filter may be measured easily for protanopes and compared with the corresponding figure for deuteranopes.[2] Table 101 and Diagram XXXI show the brightness

TABLE 101

BRIGHTNESS LEVELS OF THE R-G MIXTURES FOR PROTANOPES AND DEUTERANOPES AT DIFFERENT SETTINGS OF COLORIMETER SLIDE

		Setting of R.H. Slide in mm.								n.
		0	5	10	15	20	25	30	35	
Mean Brightness Level of R-G Mixture	% RED PROT.	100	85.7	71.4	57.2	42.8	28.6	14.3	0%	
	Adjusted to DEUT.	4.5	7.9	12.0	15.9	20.6	23.3	25.6	29.5	22
		3.2	5.6	8.5	11.3	14.6	16.3	18.2	20.9	22
	DEUT.	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9	31

of the red-green mixture at various proportions of red to green for 22 protanopes and 31 deuteranopes. It is clear that the spectrum red (slide scale setting = 0 mm.) is very much lower in mean brightness

level for protanopes than for deuteranopes, and that its brightness gradually rises as green is added, reaching the same level at 20 mm. scale reading and then becoming even brighter when the extreme green end of the scale is reached. At the extreme red end of the scale there was a scatter of brightness levels for protanopes from 1·0 to 12·0 mm., and for deuteranopes from 15·0 to 30·0 mm. As these two sets of readings do not overlap, further calculations of the statistical significance of the difference between their means is not necessary. Protanopes are undoubtedly subject to a very marked
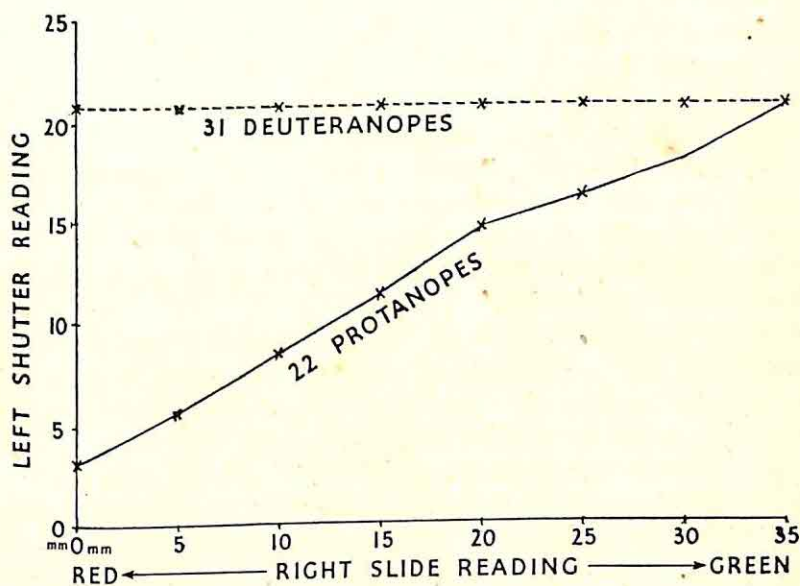
Diagram XXXI.   Darkening of Red in Protanopes

darkening of the red end of the spectrum compared with deuteranopes, and the two classes are statistically quite distinct. This was shown by von Kries and Donders and discussed by Parsons, and it is supported by data obtained by Chapanis with the Bausch and Lomb spectrophotometer.[3] The brightness level of the red-green mixture rises steadily for protanopes towards the green end of the scale, whereas for deuteranopes it does not change. Thus the protanope who had a brightness level of 12 mm. L.H. shutter reading at the R.H. slide reading of zero, rose to 35 mm. shutter reading at the extreme green end of the scale, whereas the deuteranope who had 15 mm. shutter reading at the red end still had 15 mm. at the green end. It is evident therefore that there is no danger of confusing protanopes and deuteranopes, even if the deuteranopes show a low brightness for red,

because the protanopes always show a marked increase toward the green end, however high they may start at the red end.

It is of considerable interest that protanopes show an average brightness level for spectrum green higher than that of deuteranopes. Thus for 31 deuteranopes the mean brightness level of spectrum green was 20 9 mm. shutter reading, ranging from 15 mm. to 30 mm., while for 22 protanopes it was 29 5 mm., ranging from 20 0 mm. to 35 mm. These sets of readings give a statistically significant difference between the two means, and this calls for an explanation, which is not easy to find, but may depend on the relative brightnesses of the different parts of the spectrum for the two types of red-green defectives. The standard used in these brightness estimates was spectrum yellow. For protanopes red is much darker and green considerably brighter than yellow; for deuteranopes the three colours as used in this test are of equal brightness. The latter point is very important, because it would be quite possible to make a different set of colour filters, all three of which were equally bright for protanopes. Then the red would be much brighter and the green rather darker than the yellow for deuteranopes.

If grey had been used as the standard, instead of yellow, and the same result had been obtained, then the enhanced brightness of green for protanopes might have been explained as due to a darkening of the grey relatively to green owing to the inclusion of red as one of its components. But monochromatic yellow and not grey was used. Red was not a component of the yellow standard. It was clear, however, from the factorial analysis of colour sensitivities for the nine-colour experiment, that the red sensitivity overlaps the yellow sensitivity to some extent, but not that of green. Thus a diminution of brightness of red, such as exists for protanopes, may be supposed to reduce the brightness also of yellow to some extent. This yellow standard is therefore not strictly the same for protanopes as for deuteranopes, but the green, which is unaffected by the darkening of the red in protanopes, does form an identical standard for both kinds of defectives. If we take the brightness level of green as the true standard, then we must suppose that all the brightness levels measured for protanopes are really too high, and should be lowered to the degree necessary for the brightness levels for protanopes and deuteranopes to be equal at the green end of the scale, and not at a slide reading of 20 mm. as in Table 101. The figures for protanopes, appropriately adjusted, are shown in the row below the observed measurements.

DISTINCTION OF ANOMALOUS FROM RED-GREEN BLIND SUBJECTS

Eleven of the deuteranopes require special mention because their matching ranges overstep the normal mid-matching point on the green side and do not include it. These would therefore possibly be open to confusion with green anomalous subjects. Of these eleven, 3 subjects who had the largest green deviations, also missed the normal mid-matching point by the largest amount. Their point of change from " redder " to " equality " with the yellow standard was at 22·5 mm. slide reading, whereas the normal mid-matching point was at 18·79 mm. They had, however, a matching range of 5·0 mm., whereas the largest matching range among the green anomalous subjects was no more than 3·0 mm., and the lowest point of change from " redder " to "equality" among them was 23·5 mm. Hence the distinction between moderate deuteranopes and green anomalous subjects is never difficult, though there are a few who tend to link up the two conditions.

In the same way, one subject was found who might have been classed as red anomalous instead of as a protanope. His point of change from " equality " between the red-green mixture and the yellow standard was at 12·5 mm. scale reading, while the normal mid-matching point was at 18·79 mm. He, however, had a matching range of 12 mm., whereas the largest matching range found among the red anomalous was no more than 5 mm. Again there is no real difficulty in the distinction, though certain subjects tend to bridge the gap. In general, the fact that a subject's matching range does not include the normal mid-matching point is not in itself sufficient evidence to class him as anomalous rather than colour blind. He must also have a very much smaller matching range than any red-green blind subject, and not much larger than the average matching range of the anomalous.

In carrying out these tests those subjects who might be classed in the wrong group must be examined with care, especially to determine the true limits of their matching ranges. If the range is large, their vision involves a considerable amount of red-green confusion, and they should be classed as red-green blind even if it does not include the normal mid-point. If it is small and also fails to include the normal mid-point by a very large margin, then they should be classed as anomalous. As explained before, the mode of colour change which takes place as we pass from the " redder " (or " greener ") stage through the stage of " equality " to the " greener " (or " redder ") stage is different in the anomalous and the moderately colour

K*

blind, and a careful attention to the way in which the colour names are used in doing the test by each individual will be of great assistance. The colour vision of the anomalous is like that of the normal, but very strongly deviated to the green or red side of the equation as the case may be, while the colour vision of the colour blind involves considerable (or extreme) confusion of reddish with greenish mixtures, the amount of confusion depending on the degree of the defect in each individual.

Anomalous Subjects

Fifty-three anomalous subjects took part in the four-colour test. Eleven of them were red and 42 were green anomalous. Table 102 shows that 11 green anomalous men and one woman were found by chance, while 22 men and 8 women were invited. In the red anomalous group 2 women and 8 men were invited, while 1 man was found by chance. The proportion of green anomalous

Table 102

Anomalous Subjects in the Four-Colour Test

| | Green Anomalous | | Red Anomalous | | |
	By Chance	Invited	By Chance	Invited	Totals
Men	11	22	1	8	42
Women	1	8	0	2	11

subjects found by chance in the complete sample of 217 men is therefore 5·1%, while the proportion of red anomalous subjects is ·46%. These proportions give a total of 12% of major red-green defectives in the sample of 217 men if the red-green blind are included. However, in the other experiments of this research the proportions were unduly low, and if taken altogether they even out satisfactorily in comparison with figures given by Vernon and Straker,[4] Grieve[5] and Geddes.[6] This will be discussed in the concluding chapter.

Table 103

Mid-Matching Points for Green Anomalous Subjects in the R-G Test

Mid-Point in mm.	24·5	25	25·5	26	26·5	27	27·5	28	28·5	Totals
Men G-Anom.	1	1	4	9	3	10	4	1	0	33
Women G-Anom.	0	1	0	0	0	1	3	3	1	9
Total	1	2	4	9	3	11	7	4	1	42

Table 103 and Diagram XXXII show the distribution of red-green mid-points for the green anomalous, and Table 104 and Diagram XXXII show the corresponding mid-points for the red anomalous. It will be seen that the modal red-green mid-point for green anomalous
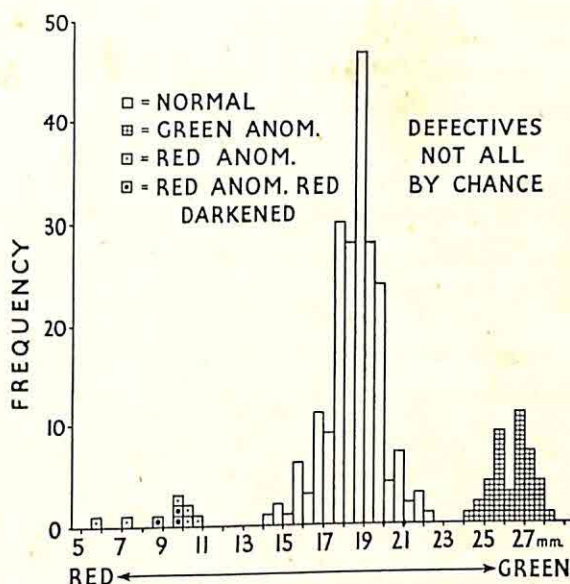
Diagram XXXII. Four-Colour Test: Red-Green Mid-Points. 206 Normal, 42 Green and 9 Red Anomalous Subjects; Half-Millimetre Steps

subjects is 27·0 mm. of scale reading. This is far beyond the most extreme deviations for normal subjects (deviants). The least extreme of green anomalous subjects had a mid-point of 24·5 mm., while the most extreme normal deviant subject has it at 22·5 mm. In the same

TABLE 104

MID-MATCHING POINTS FOR RED-ANOMALOUS SUBJECTS IN THE R-G TEST

Mid-Point in mm.	6	7·5	9	10	10·5	11	Totals
MEN R-ANOM.	1	1	1	3	2	1	9
WOMEN R-ANOM.	2	0	0	0	0	0	2
TOTAL	3	1	1	3	2	1	11

way, the modal matching point for red anomalous subjects is about 10 mm., and the least extreme of them has his mid-point at 11 mm., while the least extreme of the red deviants among normal subjects has 14·5 mm., as his mid-matching point. Hence we can say definitely

that the red and green anomalous subjects form two groups statistically separate from the normal in terms of their mid-matching points in the red-green test.

The mid-matching points for anomalous subjects in the yellow-blue test averaged 18·75 mm., ranging from 17.5 up to 23.5 mm. This mean is not statistically different from the mean mid-matching point in yellow and blue for the normal population, and the red anomalous were not statistically different from the green anomalous in this test. It is clear that anomalous subjects do not differ in deviations from normal people except in red and green.

Table 105 and Diagram XXXIII shows the red-green matching-ranges for red and green anomalous subjects. It will be seen that

TABLE 105

RED-GREEN MATCHING RANGES FOR RED AND GREEN ANOMALOUS SUBJECTS

R-G Matching Range in mm.		1	2	3	4	Totals
G. ANOM.	MEN	15	14	4	0	33
	WOMEN	4	4	1	0	9
R. ANOM.	MEN	1	2	5	1	9
	WOMEN	1	0	1	0	2

29 out of 33 green anomalous men have matching ranges of 2 mm. or less, and all the green anomalous subjects have ranges of 3 mm. or less. This distinguishes them from the red-green blind subjects, only one of whom had a matching range of less than 5 mm. in red and
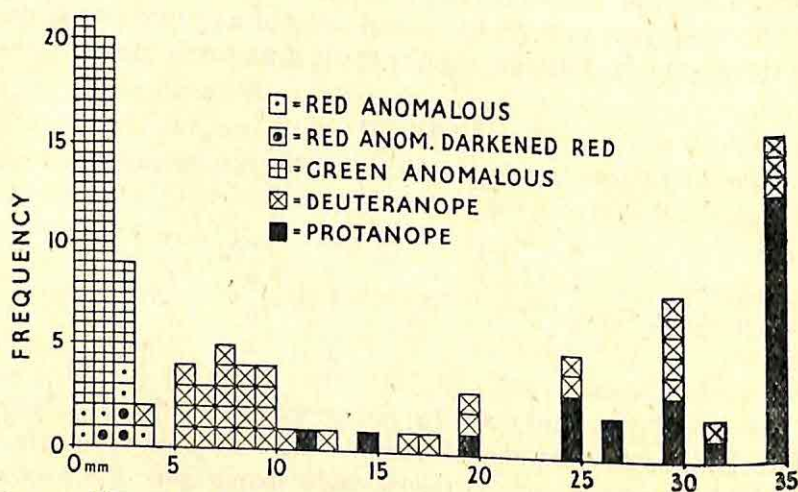
Diagram XXXIII. Four-Colour Test: Red-Green Ranges. 42 Green and 9 Red Anomalous; 25 Protanopes and 38 Deuteranopes; Millimetre Steps

green. One subject was green anomalous, but his mid-matching point in red and green was 24 5 mm., while there were several deuteranopes with green deviations as large or larger than this, who will be distinguished as " deviant " or " anomalous " deuteranopes. They were all clearly distinguished from the green anomalous subjects by the magnitude of their matching ranges, as explained in a previous section.

Two of the red anomalous subjects who had the darkened red of the protanope were classed as red-blind by the Ishihara Test. As shown previously, the average brightness level of the Ilford spectrum red filter for deuteranopes in the four-colour test was 20·9 mm. shutter reading, and does not differ from that of normal subjects, while the corresponding brightness level for protanopes was 4·5 mm. Table 106 shows the degree of darkening of this filter for

TABLE 106

DARKENING OF THE RED FILTER IN SEVEN OUT OF FOURTEEN RED ANOMALOUS SUBJECTS

Sex	R-G Mid-Point mm.	R-G Range mm.	Red Brightness Level
M	10·0	3·0	21·0
M*	13·0	1·0	20·0
M	7·5	4·0	20·0
M	10·0	3·0	20·0
M	10·5	2·0	20·0
F	6·0	1·0	15·0
M	11·0	1·0	14·0
F	6·0	3·0	7·0
M*	10·5	2·0	5·0
M	9·0	2·0	5·0
M	10·0	3·0	5·0
M*	12·0	3·0	3·0
M	10·0	3·0	3·0
M	6·0	3·0	3·0

(*From the Nine-Colour Experiment)

14 red anomalous subjects, including 3 from the nine-colour test, though the conditions were not strictly comparable. The 12 subjects may be divided into 3 groups : (a) red not darkened; (b) red slightly darkened; (c) red fully darkened. Those in group (b) are comparable with 9 normal subjects (6 at 16 mm. and 3 at 15 mm. shutter reading) in whom the red was also slightly darkened.

If therefore, we divide the 14 red anomalous subjects into groups $(a + b)$ on the one hand and group (c) on the other, we can compare them, and find that the difference between the means of these groups is significantly much greater than zero (using Student's method for small samples). In 7 of the 14 red anomalous subjects, therefore, the red is darkened to a statistically significant degree in comparison with the remainder and with normal subjects. No correlation is found either between red deviations and darkening of red or between red-green matching range and darkening of red. Correlations calculated from these figures are not of much value, but they would have to be very large indeed to be statistically significant, so that there is not the least suspicion that darkening of the red has any connection with red deviation in these subjects. This is an important point against the trichromatic theory.

One red anomalous woman was previously tested by Miss Agnes Crawford, and was a failure on the Ishihara Test, with 14/24 errors, though she was able to read all the figures in the plates which are intended to distinguish protanopes from deuteranopes, because she had red of normal brightness. The other was found by Miss M. C. Donaldson.

In the four-colour test both proved to be extremely red anomalous, having a very large red deviation and a range of no more than one millimetre. They also called the Ilford Spectrum Yellow Filter " red ", which is characteristic of the red anomalous, just as the green anomalous tend to call it " green ". The first had no known colour-blind relatives, but it is quite possible that her mother and father had both contributed genes for the red anomalous condition to her constitution, and that she was homozygous for that defect. This is suggested because it would be consistent with the appearance of no defect in either of her parents, since the anomalous condition often passes quite unnoticed, whereas had her father been a protanope, for instance, it would be more likely to have been noticed.

Later it will be seen that there are several ways in which parents of apparently normal colour vision might have a red anomalous daughter, on the two locus theory of the inheritance of red-green defects. For example, the mother might be a normal heterozygote for the green anomalous condition, and the father, as explained in discussing a similar case in Chapter VII, might carry genes for two defects together, such as green anomaly and red anomaly in different loci of his X chromosome. Such parents could have a daughter homozygous for red anomaly, but heterozygous for green anomaly at the same time, and she would probably be red anomalous.

FATIGUABILITY AS A FORM OF DEFECT

There were several subjects to whom it will be worth while to devote some attention here.

The first was a man who made four errors on the Ishihara Test, but in the red-green equation he had a matching range of 8 mm., and of 10 mm. in the yellow-blue equation. There seems to be a difference between a subject such as this, who is extremely colour weak, and those who are least colour blind, whose tendency to colour confusions is much greater, so that they make about fifteen errors on the Ishihara Test, although their matching ranges on the red-green equation might be 8 mm. or even less. He was unaware of any difficulties in daily life.

There was a very similar subject who had as big a red-green range but his yellow-blue range was much less : 4 mm. He made no errors on the Ishihara Test. A third made seven outright errors on the Ishihara Test and gave seven alternative readings where there were different figures for normal and colour blind. He had a range of 7 mm. in red and green and of 10 mm. in yellow and blue. This subject knew that he had a slight difficulty with colours, and said that while he was doing the four-colour test the spots of light tended to fluctuate much in the same way that after-sensations tend to fluctuate. In comparing the Ilford Spectrum Blue and Blue-Green filters he considered the blue-green to be " green ". In comparing the blue and violet filters, however, he called the blue filter " greenish blue " and the violet " a richer blue though not purple ".

None of these three subjects could find any evidence of colour blindness in their families, and, while the colorimeter test appears to class them as extremely weak, the Ishihara Test is indecisive or classes them as normal. A similar subject in the nine-colour experiment made one mistake in the Ishihara Test, but knew that he had slight difficulty in naming colours, especially desaturated shades in the Holmgren Wools, and had weak dark adaptation. He had a matching range of 5 mm. in the red-green test.

Another interesting subject made eighteen errors and gave two alternative readings in the Ishihara Test. His yellow-blue vision was normal, but in the red-green test he showed extremely marked fatiguability. He started the test with a small range and a deviation of about 5 mm. to the green side. This, coupled with the Ishihara Test result, raised suspicions that he might be anomalous. As the colorimeter test proceeded, however, his red-green discrimination rapidly weakened, and after three ascending and descending series of readings

his deviation became almost zero and his matching range increased to 8 mm. He was very short-sighted, but this is never sufficient to account for an abnormal colour test result, especially when corrected by glasses as it was in this subject.

In all these cases it seems that we are dealing with a form of defect slightly different from ordinary colour weakness on the one hand and from colour blindness on the other. It certainly cannot be confused with anomalous colour vision, but might be explained best as due to rapid fatiguability of red-green discrimination. Such fatiguability is certainly also present among some of the anomalous and colour-blind subjects, but it is not a general characteristic of them. Marked fatiguability might be an additional form of colour-vision defect, and the fact that all the cases brought forward here to illustrate it were men, hints at the possibility that it might be sex-linked. In order to test this possibility, it would be necessary to find how many women showed a similar defect, first proving that they were not heterozygotes for red-green blindness or anomalous colour vision.

From the point of view of practical colour-vision testing, however, it is important that every individual who has an exceptionally large matching range (or deviation) in the red-green test should also be given the Ishihara or Stilling (or some similar) Test. A tendency to make fifteen or more errors in the Ishihara Test favours the view that the person had an ordinary sex-linked red-green defect, whereas so few as six or fewer errors favours the view that he is simply an extremely colour-weak subject belonging to the normal population. If, however, rapid fatiguability is actually observed and even measured in the colorimeter, it may be evident that this is the true cause of defect, whatever the result of the Ishihara Test. Fatiguability is therefore a clinical sign for which we should always be on the look-out when testing, and, if it is found, an effort must be made to distinguish between it as the main cause of defect and its incidental appearance as added to red-green blindness or anomalous colour vision. Hence a rating for fatiguability should be given for every individual who is classed as having any marked form of abnormality of colour vision. In difficult cases it would appear that great clinical skill is called for, especially if the subject being tested is temperamentally difficult, but fortunately such subjects are seldom found. Whether the tester is fully satisfied that he has drawn a distinction between fatiguability, colour weakness and a major red-green defect in any given case, however, all subjects concerning whom there are serious suspicions of extreme fatiguability for red-green vision should be

classed as "unsafe", especially if they have abnormally large matching ranges in yellow and blue as well as in red and green.

SEX DIFFERENCES

It has been shown in previous chapters, and in letters to *Nature*,[7, 8] that women with known colour-blind relatives were significantly more often red-green weak to a slight extent than women taken at random. This carries the implication that red-green blindness must be an incompletely recessive Mendelian character (though sex-linked), because a large proportion of the women with colour-blind relatives must be heterozygotes for the defects in question. Ford[9] has listed red-green blindness as a sex-linked recessive with occasional heterozygous manifestation. He explains that there is "some evidence that the gene for colour blindness is at least partly expressed in the heterozygotes. Its frequency in women is therefore above expectation ".[10]

In the present experiment there were 191 men and 185 women with normal colour vision (but otherwise chosen at random), and 18 women with known colour-blind relatives. The subjects were grouped to compare men with women selected at random, and these women in turn with the women who knew of colour-blind relatives. The chi-squared technique showed that there was a higher proportion of women than of men in the random samples, who had more than twice the modal red-green matching range, on a probability level of less than 0·001, although the modal matching range was the same for both sexes. Similarly, there were more women with twice the modal red-green matching range among those with known colour-blind relatives than among the random sample of women, on a probability level of less than 0·01. In yellow-blue vision there were no significant differences in matching ranges, either between men and women taken at random or between women at random and women with colour-blind relatives.

If we take Vernon and Straker's[4] figure of 7·31% of major red-green defectives among the men in Glasgow and the West of Scotland, which seems to be a likely proportion compared with other estimates for their frequency among white people,[5, 6] we may assume the truth of the single locus theory, which will be reconsidered in Chapter X, and expect about 13·57% of heterozygotes for sex-linked defects among the population of women for the same area.[11] In a sample of 185 women taken at random, we should expect about 25 heterozygotes. In the random sample of 185 actually tested in this

experiment there were 18 more women with over twice the modal red-green matching range (not of course, the 18 women with colour blind relatives) than there were men with more than twice that range in the sample of 191 men. This proportion does not differ significantly from the 25/185 heterozygotes expected, and it therefore confirms the reliability of the test. In selecting women with more than twice the modal red-green matching range we are picking out a great proportion of the heterozygotes. Since there were 40 women with that matching range in the sample of 185, and 22 men in the sample of 191 men, the chances that any given woman with twice the modal red-green range is a heterozygote will be about 1 in 2. This shows that although the test is a useful guide, where a woman might be suspected of being a heterozygote, it is not capable of detecting individual heterozygotes with any reliability. There is some evidence that women are more often blue and men more often yellow deviants, but apart from this no sex differences were found in ranges or mid-matching points for yellow-blue vision or in mid-matching points for red-green vision.

" Dark " and " Fair "

The subjects tested were all classified at the time of doing the test into two groups, " dark " and " fair ", on the basis of the predominant impression of skin and hair pigmentation. In the whole group tested (including some additional subjects not included in the calculations previously mentioned) there were 181 dark (94 men and 87 women) and 224 fair (98 men and 126 women) making up 405 in all, excluding major red-green defectives. This suggests that women are more often fair than men, but the difference is not sufficient to be statistically significant. All these subjects' points of change from " redder ", " greener ", " yellower " and " bluer " than the standard spot on the four-colour test to " equality " with it were then grouped, each set of points into two categories, high and low, in four tables showing how many subjects in each category for each colour were dark and how many fair. In this way it was possible to compare the proportions of fair and dark who had and had not any weakness in each of the four colours tested. No significant differences were found for any colour, though there was a statistically insignificant tendency for the fair to be weaker than the dark in red and blue. As far as normal subjects are concerned, therefore, no evidence favouring the hypothesis that pigmentation is connected with colour-vision defect was found.

In order to test more carefully the hypothesis that darkness of pigmentation may be connected with colour-vision weakness, the colour blind and anomalous subjects were also classified into " dark " and " fair " like the normal subjects. The proportion of dark to fair among them was found to suggest that more fair than dark were major-red-green defectives, but the difference from the proportion of dark to fair in the normal population was not significant. It was concluded that fair subjects are as often major red-green defectives as dark.

RACIAL DIFFERENCES

The Jewish and non-European subjects shown in Table 107 were given the four-colour test. These subjects were then grouped

TABLE 107

JEWS AND NON-EUROPEANS IN THE FOUR-COLOUR TEST

	Jews	Indians	West Africans
MEN	2	0	10
WOMEN	7	2	1

according to the magnitude of their matching ranges, and compared with 191 normal men. No differences sufficient for statistical significance were found between the group of 22 subjects shown in the table and the normal men either for red-green or for yellow-blue matching ranges. If, however, the West Africans were taken as a separate group, they were found to be significantly more often yellow-blue weak than the men in the European group of 191 subjects.

The Jews and Indians in one group and the West Africans in another group were then compared with the normal European population in respect of mean matching points. There were no differences. These groups were also compared with the European group in respect of differences between the standard deviations of red-green and yellow-blue mid-matching points. Again no significant differences were found.

THE COLOUR VISION OF CHILDREN

A survey of children mainly from Glasgow, Ayr and the South West of Scotland was undertaken by Mr. Robert Brown. This had two main aims : (1) to apply the Ishihara Test to as many children as possible in order to compare the proportion of major

red-green defectives with the percentage in the adult population, and (2) to test a number of the children with the colorimeter in order to compare their red, yellow, green and blue vision with the colour vision of adults.

Mr. Brown found that there was no difficulty in persuading children to take part in the research, though with the younger children there was some difficulty in establishing rapport for the tests.

There was a considerable language difficulty, especially in the use of the words " brightness " or " intensity " and " same ". For most of the children the phrase " when there are no differences in brightness " had no meaning. This difficulty was overcome by asking, " What is happening to the right-hand spot of light ? " as it was reduced in intensity until almost completely shut off and then increased again. One or two such movements were usually sufficient to find a word which implied brightness. Throughout the rest of the experiment the word preferred by the child being tested was then used.

The children's difficulty with the word " same " was that they tended to imply without differentiation " same brightness " or " same colour ", and in so doing they took no account of shade used in the sense of slight variations of hue. This difficulty was surmounted by asking near the beginning what was the colour of the left-hand spot (in the red-green test). For example, if the response were " green " (rather than yellow), later when the colour of the right-hand spot was also green the child was asked if the two spots were the same green. In cases of extreme difficulty the colours of the child's shirt, vest, tie, jacket, etc., were used to settle the point at issue.

The lower limit of the child's ability to do the tests probably depended on schooling and intelligence. It was not found possible to give children below five years of age the Ishihara or Colorimeter Tests, and the precise limits due to schooling and mental age would have to be determined by a separate research. Among the children tested here reliable results were obtained above about five and a half years of chronological age and with about two months of schooling. Those children below the five and a half year level are probably less reliable, but are included in Table 108 for the sake of completeness.

Among those children who did the Ishihara Test thirty-nine boys and one girl were found who were major red-green defectives, making 7·43% of boys and 0·46% of girls. These proportions do not differ from the percentages found among adults in the same parts of Scotland, and show that red-green major defects are not more frequent among children than among adults. With the colorimeter the

proportions of different types of major defectives shown in Table 109 were found.

In order to test the possibility that minor colour defects might be more common among children than among adults, which was

TABLE 108

NUMBERS OF CHILDREN TESTED BY MR. ROBERT BROWN WITH ISHIHARA AND COLORIMETER

AGE:	NUMBERS OF CHILDREN TESTED						TOTALS		
	5 to 5½		5½+ to 11		11+ to 15+				
SEX:	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Both
Ishihara only :	50	30	269	123	125	63	444	216	660
Ishihara and Colorimeter :	13	12	41	13	27	11	81	36	117
TOTAL ..	63	42	310	136	152	74	525	252	777

suggested by Tucker's work with Lovibond's Tintometer, comparisons were made with the adult populations who did the four-colour test, excluding major red-green defectives. It was found by the Chi-squared test, that there were no significant differences from the

TABLE 109

FREQUENCIES OF MAJOR DEFECTIVES AMONG CHILDREN : 81 BOYS AND 36 GIRLS. *INVITED (SISTERS OF GREEN ANOMALOUS GIRL FOUND BY CHANCE).

AGE:	5 to 5½		5½+ to 11		11+ to 15+		TOTALS	
SEX:	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls
Protan.:	1	0	1	0	1	0	3	0
Deuteran.:	0	0	1	0	2	0	3	0
G. Anom.:	0	0	1	2*	0	1	1	1+*2

adult frequencies, in the proportions of boys or girls in either of the age-groups, 5½ + to 11, or 11 + to 15 +, who had two or more times the modal matching ranges in the red-green or in the yellow-blue tests. The distributions of deviations in the red-green and yellow-blue tests were tabulated for boys and girls separately, in both the age-groups mentioned above, and these did not differ significantly from the corresponding distributions for adult subjects. In general

it was concluded that the colour vision of children down to about five years of age does not differ in any way from that of adults.

FACTORIAL ANALYSIS OF COLOUR SENSITIVITIES

As in the previous experiments, intercorrelations were worked out between colour weaknesses, the measurements being taken from the zero (or maximum) of the colorimeter slide scale to the point of change from " redder ", " yellower ", " greener " or " bluer " than the standard to " equality " with it. Similarly brightness levels were measured for each subject at the normal mid-matching point for each colour pair, and these were intercorrelated with the colour sensitivity measurements, the effect of the unwanted colour being partialled out. This gave a 6×6 table of intercorrelations which was factorised with the result shown in Table 110. Here the brightness level measurements were intercorrelated with the colour sensitivity measurements and factorised together with the other intercorrelations, instead of being grafted upon the table of colour sensitivity factor loadings after the main factorisation.[12]

TABLE 110

FACTOR-LOADINGS IN THE FOUR-COLOUR TEST : 357 NORMAL SUBJECTS

Colours and Brightness Levels	Factor Loadings		
	I	II	III
RED	·070	+ ·767	− ·226
YELLOW	·007	+ ·104	− ·451
GREEN	·121	− ·683	− ·069
BLUE	·459	− ·061	+ ·236
Y-B Brightness	·179	− ·268	+ ·395
R-G Brightness	·252	+ ·141	+ ·115

This table confirms previous results. The general factor is small, and, as in the nine-colour experiment, it is most heavily saturated with blue sensitivity. The first bipolar factor gives a strong contrast between red and green, yellow and blue being almost negligible. The second bipolar factor contrasts yellow and blue. It is interesting that the general pattern of factors should be the same as in the nine-colour experiment, and that the presence of the yellow-blue factor is confirmed. The brightness level loadings require some care in their interpretation. In the general factor it is clear that brightness level is mainly correlated with blue. Loss of sensitivity to blue corresponds to loss of brightness. This might be interpreted by

saying that when blue loses saturation it becomes darker, or by saying that loss of blue saturation and loss of brightness are not effectively discriminated by the subjects of the test. In the first bipolar factor the main links are between red and the red-green brightness level, and between green and the yellow-blue brightness level. In so far as brightness is affected by the red-green factor, we may say that loss of saturation of red corresponds to loss of brightness in the red-green axis, while loss of saturation in green corresponds to loss of brightness in the yellow-blue axis. In the second bipolar factor both brightness levels correspond to loss of blue saturation. A general interpretation of the brightness level saturations might be as follows : Loss of saturation of blue and to a lesser extent of green tends to be identified with or causes loss of brightness; loss of saturation of red has a small effect of the same kind; loss of saturation of yellow has the opposite effect to a moderate degree.

Such an interpretation would support the general observation that subjects with blue weaknesses tend to confuse blue with dark grey, and this is to a lesser extent also true of green and red, whereas subjects with loss of yellow sensitivity tend to confuse yellows with light greys or white. On the whole, however, the brightness saturations are small, and there is good reason to think of brightness as determined independently to great extent, though it is linked with blue more than with any colour.

Brightness and Saturation of Red, Yellow and Green in Red-Green Defectives

In this experiment protanopes, deuteranopes and anomalous subjects were given tests measuring the saturation of red, yellow, green (and blue, which was not used in the present calculations), and of the photopic brightness levels of these colours as represented by the corresponding Ilford Spectrum filters. Correlations were worked out by the product-moment formula between red and green, red and yellow, and green and yellow saturations, for all groups except the red anomalous, and by the rank difference formula for them. Similar correlations were worked out between red and its brightness level for protanopes and the red anomalous, and between green and its brightness level for deuteranopes and green anomalous subjects. These correlations are shown in Table 111. Those marked with an asterisk are statistically significant on the 0·01 level.

The correlations between saturations and brightness levels are not significant even on a lenient level, though all are positive. They

do not provide any evidence that the degree of loss of saturation of the hues in question are directly related to the brightness levels of the same hues for these groups of defectives.

It is true that protanopes as a group have the red end of the spectrum extremely darkened in comparison with deuteranopes and green anomalous subjects, but the variations of this loss of brightness are not proportional to the corresponding losses of red saturation.

TABLE III

BRIGHTNESS AND HUE SATURATION CORRELATIONS FOR MAJOR R-G DEFECTIVES

(*Significant on 0·01 level)

N	Subjects	Tests		Corr.
24	Protanopes	R and G saturation	..	+·652*
		R and Y saturation	..	—·228
		G and Y saturation	..	—·002
		R and its brightness	..	+·182
36	Deuteranopes	R and G saturation	..	+·458*
		R and Y saturation	..	+·167
		G and Y saturation	..	+·094
		G and its brightness	..	+·276
38	Green Anomalous	R and G saturation	..	—·589*
		R and Y saturation	..	—·034
		G and Y saturation	..	+·077
		G and its brightness	..	+·143
14	Red Anomalous	R and G saturation	..	—·412
		R and Y saturation	..	—·021
		G and Y saturation	..	+·149
		R and its brightness	..	+·383

The correlation between red and its brightness is not significant for the red anomalous. In deuteranopes and green anomalous subjects, among whom green is not darkened relatively to the normal, although greatly desaturated, there is still no correlation between this loss of saturation and the variations of its brightness level.

These facts create considerable difficulties for the Young-Helmholtz theory, or any three-colour theory on which saturation and brightness variations for primary hues should be perfectly correlated. Other writers have attempted to meet these difficulties, particularly

Piéron,[13] and the facts here reported are entirely in accordance with the factorial analysis of colour vision and brightness level variations of normal subjects and with Granit's data based on electroretinography.[14]

Further difficulties for the Young-Helmholtz theory are created by the positive correlations between red and green saturation losses among protanopes and deuteranopes, which are significant on the 0·01 probability level, and which confirm the view that these subjects are not to be regarded as " red " and " green " blind, but both as red-green blind, as pointed out by Rivers[15] in 1900 and by Rayleigh[16] in 1881, in spite of which the terms " red " and " green " blind still persist. The difference between the red-green blind and the anomalous subjects is well brought out by the fact that the correlation between red and green saturations among them is negative and significant, as it is among normal subjects.

On the Young-Helmholtz theory it is equally difficult to understand how it can be that no correlations appear between either red or green and yellow saturations for any of the groups of major defectives. This again confirms what has been found among normal subjects. Although according to this theory yellow should be produced by the combined effect of red and green sensations, its saturation varies independently of losses of red and of green among all major red-green defectives as well as among anomalous subjects and the normal population.

Facts such as these, which appear to be incompatible with the Young-Helmholtz theory, will be found to accord readily with expectations based on a four-colour theory in which red-green and yellow-blue receptors operate in two pairs, and in which photopic brightness is determined at least to a large extent by an independent system.

BINOCULAR COLOUR COMBINATIONS

The results of factorial analysis of the ratings for completeness of fusion of nine colours in binocular combination, made by thirteen normal and abnormal subjects according to the technique described in Chapter 1, are shown in Table 112. These subjects all took part in the four-colour experiment. The factors are interesting because they show which colours are most and which least difficult to combine binocularly, by subjects with seven different types of colour vision, the ratings of the normal subjects being averaged before factorisation. It would be unwise to try to draw definite conclusions from these figures without more extensive experiments first.

The general factor shows that all nine colours have a considerable binocular combining tendency, about the same for all types of colour vision. Blue-green has the greatest combining tendency for all subjects except the green anomalous and the red anomalous with red of normal brightness, and for them yellow had the heaviest loading. The colour least easily combined with others varies from

TABLE 112

BINOCULAR COLOUR COMBINATIONS: Seven Normal and Six Defective Subjects (Decimal Points Omitted)

Type of Subject	Factor	Colours Combined								
		R	O	Y	YG	G	BG	B	V	P
Average of 7 Norm's	I	735	687	794	806	796	861	785	738	723
	II	+535	+407	−132	−439	−547	−306	−039	+141	+481
	III	−284	−598	−559	−175	−065	+260	+595	+584	+241
Green Anomalous	I	737	804	925	839	845	891	764	828	858
	II	−188	−350	−265	−264	−412	+383	+576	+414	+208
	III	+592	+152	−157	−481	−208	−165	−136	+162	+233
Dev'nt Deuteranope	I	701	775	805	775	789	924	641	686	612
	II	−308	−566	−504	−378	−447	+400	+666	+603	+544
	III	+453	+266	−239	−309	−322	−176	−060	−242	+630
Ordin'y Deuteranope	I	823	726	850	876	876	918	754	781	696
	II	−393	−519	−451	−234	−344	+152	+593	+551	+636
	III	+189	+302	−134	−313	−096	−159	+237	+065	−089
R. Anom Normal Red	I	653	759	851	791	821	805	607	653	639
	II	−414	−593	−522	−432	−417	+494	+710	+616	+559
	III	+543	+236	−053	−463	−537	−059	+158	+079	+097
R. Anom Dark'd Red	I	633	798	827	826	841	913	712	668	799
	II	−471	−613	−564	−400	−314	+315	+742	+763	+549
	III	+479	+074	+061	−351	−414	−319	+001	+216	+253
Protanope	I	694	746	759	721	662	849	678	682	759
	II	+124	−188	−192	−141	−193	+127	+140	+177	+107
	III	−496	−146	+233	+317	−303	+222	+245	+128	−199

orange in normal subjects, to red in the green anomalous, purple in the deuteranopes, blue in the red anomalous with red of normal brightness, red in the red anomalous with darkened red and green in the protanope.

The first bipolar factor shows that for normal subjects colours of the red-green groups are more difficult to combine binocularly than yellow-blue colours, while the second bipolar shows that in a

minor way yellow-blue colours are more difficult than reds and greens. Thus, when the general combining tendency and the red-green difficulty have been eliminated, there remains the difficulty with yellow and blue, and this, of course, is linked up with the probability of a difficulty with colours of widely different brightnesses, but since we have not done an experiment with greys of equal and differing brightnesses this is not certain. Both bipolar factors show that primary opposite colours are more difficult to combine than neighbours on the colour circle.

For all the red-green defectives the reversal of the order of the bipolar factors shows that the yellow-blue colours are more difficult to combine for them than the red-green groups. For normal subjects the yellow-blue colours are difficult, but reds and greens more so; for the red-green major defectives the position is reversed. The red and green anomalous subjects are alike on the whole, which shows that this experiment is not a test sensitive enough to distinguish between them. For the green anomalous the red-green factor is tilted in the direction red to yellow-green. The deviant deuteranope differs from them in the narrowing of the scope of the red side of the red-green factor, which for him includes only purple, red and orange, and is tilted in the direction of purple to yellow-green. The green side of this factor tends to be narrowed in the red anomalous.

In the protanope and the ordinary deuteranope certain opposites are coupled in the red-green factor. Purple is united with green for the deuteranope while green is united with red for the protanope. This corresponds with the well-known facts that purple and green both tend to be colourless for the deuteranope, while red and green (though it is usually blueish green) tend towards grey for the protanope. These opposites are therefore combined more easily in binocular pairs than either colour of each pair is combined with its neighbours.

This experiment supports the four-colour theory by showing that even in major red-green defectives the contrasting functions of the red-green and yellow-blue receptor systems are not lost. The balance of their contribution to colour contrasts in visual experience is tilted heavily towards yellows and blues, however, as shown by the factorial analysis of colour sensitivities in Chapter 7, and illustrated diagrammatically in colour in the Frontispiece. Although reds or purples and green combine easily for the colour blind, they unite in contrast to yellows and blues, and this is evidence that their receptor systems continue to operate. For the anomalous the capacity for red-green differentiation is still present although it

takes a minor place for them in comparison with the place it takes for those with normal colour vision.

In consequence we may say that the combining tendency of reds (purples) and greens for the colour blind, which corresponds to their difficulties in daily life in distinguishing these hues, must be explained in terms of the relative failure of the receptor system to react differentially to the light waves in question. Since there is this failure, both stimuli tend to be represented by yellow sensations, but this does not mean that either the red or the green receptors are out of action, because this would not produce sensations indistinguishable from yellow. Similarly, the combining tendency of purples or reds and greens in the defectives does not lead to the inference that yellow in the normal is produced as a sensation only by the additive effects of red and green responses, since yellow is still present as an independent factor in the red-green blind.

RELIABILITY

In order to gain an estimate of the reliability of the four-colour test 36 of the subjects (16 men and 20 women) were re-tested with exactly the same technique. The interval between testing and retesting varied between two hours and two years, and no connection was found between length of interval and reliability on the re-test. Of these subjects two men and one women were green anomalous and one man was red anomalous, while one man was an extreme protanope. Ordinary inspection showed readily that the test was not less reliable with these subjects than with those having normal colour vision. In addition two men and one woman had extreme weaknesses in yellow, but the test was not less reliable with them than with normal subjects. The coefficients of reliability are shown in Table 113. All the colour correlations were calculated between the points of change from " redder ", " greener ", " yellower " or " bluer " than the standard to " equality " with it in the two tests. The brightness coefficients were calculated between the brightness levels of the colour pairs in question at the average mid-matching point. All the coefficients are well above the level for statistical significance on a probability of 0·01, for the number of subjects tested.

The coefficients are reasonably high, especially those for red and green, which are certainly the most important from a practical point of view. In the red test 28/36 readings were unchanged on the re-test; in the green test 19/36; in both the yellow and blue tests 14/34, and most of the changes which did occur were very small.

Reliability coefficients as low as ·6 are not sufficiently high for complete confidence to be placed in the test, and it would be an advantage if the yellow-blue test could be improved still more. The first difficulty with the yellow-blue test is that variations in yellow and blue saturation are easily confused by the subjects with brightness variations. It is doubtful if any improvement in the test can overcome this difficulty, which would still hold, even if a yellow and blue filter of quite equal brightness were used. A second difficulty is the

TABLE 113

RELIABILITY COEFFICIENTS IN THE FOUR-COLOUR TEST

Test	Reliability Coeff.	N
Red	·930	35
	·978	36
Green	·969	36
Yellow	·611	32
	·925	34
Blue	·687	34
R-G brightness	·610	36
Y-B brightness	·736	34

readiness with which yellow and blue combine to produce grey, and, indeed, this is perhaps essentially linked with the first difficulty. The matching range is therefore always rather large in yellow and blue, and more reliable results might be obtained by any technique which reduced it. For this two possibilities might be exploited : firstly that larger steps might be taken for all subjects in doing the yellow-blue test, and this possibility could be explored experimentally; secondly that the yellow and blue pair might be changed slightly so that they matched a standard of distinct hue, say green or pink, instead of pure grey. For example, violet and yellow or orange and blue would match a faintly pink standard, while yellow-green and blue or blue-green and yellow would match a faintly green standard. Then the hue discrimination introduced might sharpen the points of change and give the subject a steadier result. A test of violet has much to recommend it, though violet is such a dark hue that a rather polychromatic filter would have to be used (such as the Ilford Spectrum Violet), and of the four possible pairs mentioned as alternatives to yellow and blue it is likely that yellow and violet matched against a pink standard made by mixing some red with the neutral grey would be the most useful. The nine-colour experiment suggested

that a test of violet and yellow-green would be less revealing of yellow-blue defects than the simple yellow-blue test. The violet-yellow test has not been studied.

RELATION WITH THE ISHIHARA TEST

In order to compare results obtained with the Four-Colour Test and the Ishihara Test a number of red-green blind, anomalous, colour-weak, deviant and normal subjects were tested with the 25-Plate version of the Ishihara Test (Japanese printing) as well as with the Four-Colour Test. The results of the two tests are shown in Table 114. The protanopes and deuteranopes are divided into moderate and

TABLE 114

NUMBERS OF ERRORS MADE ON THE ISHIHARA TEST BY VARIOUS SUBJECTS

SUBJECTS CLASSIFIED BY THE FOUR-COLOUR TEST		ISHIHARA TEST RESULT:		
		Average No. of Errors	Scatter	Number Tested
PROT:	Moderate	20.5	18—23	3
	Extreme	24	0	15
DEUT:	Moderate	21	4—24	19
	Extreme	24	0	5
GREEN ANOMALOUS		18	8—24	25
RED ANOMALOUS		22	14—24	11
DEVIANTS		3.5	0—8	18
COLOUR WEAK		4.5	0—12	14
NORMAL		3.5	0—8	11

the division being made at a matching-range of about 16 mm., those with a larger range than this being classed as extreme. This was a satisfactory dividing line because there were few subjects with ranges of about this magnitude. The subjects with deviations of 2 × sigma or more were classed as deviants (anomalous subjects taken separately), while those with matching ranges of more than twice the modal range were classed as colour weak. Two of the subjects listed were both colour weak and deviant on these principles and were in consequence counted twice over, but they both made fewer than the average number of errors on the Ishihara Test.

It will be seen that the Ishihara Test fails all extreme deuteranopes and protanopes with 24 errors out of 24. Moderate protanopes and

deuteranopes tend to make rather fewer errors, but cannot be distinguished satisfactorily on the Ishihara Test from the subjects with extreme defects, because a considerable number of them also made 24 errors, and the one who made only 4 errors was very exceptional. Apart from him the smallest number of errors made by a colour-blind subject was 13. The anomalous subjects, again, are distinguished neither from the extreme nor from the moderate protanopes and deuteranopes. Seven out of eleven red anomalous subjects made 23 or 24 errors, and only five green anomalous subjects made fewer than 17 errors. Hence the Ishihara Test does not clearly separate these groups of red-green defectives.

The colour weak made an average of 4.5 errors, while the deviants made an average of 3·5 with one exception at 8 errors. These types, clearly distinguished by the four-colour test, are not satisfactorily separated by the Ishihara Test from the normal subjects, who made on the average 3·3 errors with one exceptional subject at 8 errors.

In general, the conclusion may be drawn again, that the Ishihara Test is an effective cut-out mechanism which fails all major red-green defectives (with a few exceptions) and passes all normal, colour-weak and deviant subjects (again with a few exceptions). If a failure level of at least 12/24 errors be required, then it may be assumed that very few will be failed who ought to have passed and very few passed who should have failed. It is still an important and difficult question how many colour-weak and deviant subjects, who would pass the Ishihara Test, ought to be considered as dangerous or slightly dangerous in occupations involving the use of red-yellow-green signal systems, and what sorts of duties they might have a difficulty in performing. Such a problem can be settled only by careful experimentation.

A further interesting point about the Ishihara Test is its relative inability to distinguish decisively between those subjects with and those without the darkened red of the protanope. Seventy-nine colour-blind and anomalous subjects did the Ishihara Test, and Table 115 shows that for only 33 of them was the Ishihara Test decisive in respect of the distinction mentioned. That is to say, no more than 13/24 deuteranopes, 4/19 protanopes, 11/25 green and 5/11 red anomalous subjects were decisively and correctly classified as having or not having darkened red. It would seem therefore that estimates of the relative numbers of protanopes and deuteranopes based on the Ishihara Test may be very unreliable. This is a conclusion supported by data given by Chapanis,[3] and is to be expected, because the Ishihara Test does not provide a variable darkness of

grey with which to compare the red being tested, whereas the degree of darkening of the red end of the spectrum is very variable in different protanopes (though the red is always much darker than it is in deuteranopes). In addition, about one half of the number of red anomalous subjects do not have the red of the spectrum darkened, and the Ishihara Test fails to distinguish them from deuteranopes though their colour vision is completely different.

TABLE 115

INDECISIVENESS OF THE ISHIHARA TEST IN DISTINGUISHING DARKENED AND NORMAL RED

Subjects		Decisive	Indecisive	Totals
DEUT :	Moderate	10	9	19
	Extreme	3	2	5
PROT :	Moderate	0	4	4
	Extreme	4	11	15
Green Anomalous		11	14	25
R. ANOM.:	R. Normal	3	3	6
	R. Dark	2	3	5

Finally, two typical green anomalous subjects were tested, both of whom were extreme blue deviants, with yellow-blue matching points of 25 mm., and ranges of 1·0 mm. Of these the first had been tested several times in the R.A.F., and was classed as " colour blind " on the pseudo-isochromatic tables, and as " defective-safe " on the lantern test. At first he had been passed. The second was passed by the R.A.F. in 1941, and became a pilot. In the laboratory the first made 20 errors on the Ishihara Test, but the second made only 9 errors, and, unless some hesitation had been noticed, he would probably have been passed with normal subjects in the first and quick survey of a class of about 90 students. It seemed that his capacity to read the figures in the Ishihara Test was due to the blue deviation, because he then read them through a daylight blue filter, which restored the balance in his yellow-blue vision by subtracting yellow, and made 24 errors and was a complete failure on this test. With the first subject, however, this explanation did not apply because he already made 20 errors without the blue filter, and so we see the inadequacy of the Ishihara Test in a critical situation. It passed one green anomalous man because he had an extreme blue deviation, which made the orange dots more visible to him than is usual with these subjects, but with another, almost exactly the same, the effect

was different for unknown reasons. If the critic suggests that the fault may have been with the Four-Colour rather than with the Ishihara Test, then it must be said that the green anomalous condition is extremely marked and could not possibly be mistaken for anything else except perhaps for that of a very deviant deuteranope who had a small matching range, and he would be even more defective. Undoubtedly the confusion was due to the Ishihara Test.

PRACTICABILITY OF THE FOUR-COLOUR TEST

It will be useful at this stage to point out the advantages of the four-colour test as a practical instrument. They are as follows :—

1. It is of simple construction and can be made in standardised form out of easily obtainable materials.

2. It is portable and can be set up in any room which can be darkened and has a normal electricity supply. It could be adapted without much difficulty to use with motor-car batteries and would then be independent of the electric mains.

3. The technique of testing is a simplified form of the limiting method, and can be learned easily by anybody. So long as the standardised technique is applied, and no liberties are taken except those specifically allowed, the results of testing by different individuals will be comparable.

4. Each subject can be compared directly with the standard tables of scores representing the results for the population at large. In this way the well-established principles of individual psychology, as employed in intelligence testing, can be applied to colour vision.

5. The test efficiently differentiates colour-weak and deviant individuals in the normal population, and distinguishes protanopes, deuteranopes, red and green anomalous subjects clearly from the normal group and from each other.

6. The test compares the normal population with major red-green defectives on the same scale.

7. The red-green part of the test is very reliable, and the yellow-blue part less reliable, but both parts are valid in the sense that they measure the four colours which have been shown to be the principal variables in human colour vision.

8. For shortening of the test the yellow-blue part may be omitted where red-green vision is the only concern of the tester.

9. With all normal subjects the whole test can be carried out in 10 to 15 minutes. Some colour-defective individuals require longer, and in order that they should feel that they have been

adequately dealt with they should be given an additional test, such as the Ishihara.

10. The Four-Colour Test can be applied to children over five years of age.

Taking all these points into account the difficulties of using the test are less than the difficulties of using other standard colour tests, while the efficiency, reliability, validity and scientific adequacy are vastly superior. It is also much more competent as an instrument for scientific research on colour vision than any colour test known to the writer.

Chapter 10

GENERAL CONCLUSIONS

IN this chapter a general summary will be given of the experiments and the conclusions to be drawn from them. In all, more than 1,100 individuals were examined by tests based upon the Rayleigh equation and by other tests where opportunity offered. All these subjects were tested individually and many of them were questioned in detail about their experiences with colour in everyday life. This number included 155 men and 23 women who were major red-green defectives. A proportion of the defectives were obtained by chance and the remainder were invited. The colour vision of relatives was studied wherever possible. The central aims of the research were: (a) To set up tests by which individuals with all types of colour vision could be compared according to the accepted methods of the study of individual differences in psychology; (b) To examine the bearing of the results upon the problems of theory; (c) To study the inheritance of individual differences of colour vision.

PROBLEMS OF TESTING COLOUR VISION

In colour vision we are presented with a problem not met with in other branches of psychology such as intelligence testing which are more familiar. Generally the variations to be measured are grouped in a normal distribution with a fairly large standard deviation, like intelligence quotients. Intercorrelations between tests are for the most part positive. Thomson points out that this would be expected, because ability at one task tends to be coupled with at least some ability at others.[1] One of the psychologist's greatest problems— perhaps still unsolved—has been that of separating abilities. In colour vision, however, the majority of individuals vary little amongst each other and are almost equally sensitive, so that the standard deviation is very small and a test effectively separating them is very difficult to make. About 7% or 8% males among Whites are extremely different from the majority, and actually form six sub-groups, all of which are extremely different from each other. Correlations combining these statistically distinct groups would not have any meaning, and

the groups must be dealt with separately. At the same time, correlations worked out for the statistically uniform groups are often strongly negative, as between measures of red and green sensitivity. In consequence, on the one hand the population is split up into at least seven sub-groups, and on the other hand there is little general ability for colour discrimination and we cannot say that capacity to distinguish red will predict capacity to distinguish green, yellow or blue, as we can say that the ability to express the meanings of words will predict (to a great extent) capacity for problem solving in general. Thus the differentiation of verbal and practical abilities from general intelligence is a completely different problem from that of separating colour-vision variations. General intelligence is largely undifferentiated, but has certain minor sub-divisions, while colour sensitivities are highly differentiated but based on a small generalised component.

While the discontinuous nature of colour vision variations has made certain special difficulties for the tester, it has also made crude colour-vision tests possible. There is a gap between normal subjects (including the deviant and colour weak as defined in this book) and those who have major red-green defects. The common tests of colour blindness operate at the level of this gap, and among them the wools, beads and probably the lantern tests are relatively less and the pseudo-isochromatic tables are relatively more efficient. The general effect of these tests is to separate the normal, deviant and colour weak from the anomalous and the colour-blind subjects. The less efficient tests tend to group the anomalous subjects with the normal, while the more efficient group them with the colour blind. Unless this gap were a prominent feature of colour-vision variations, such crude tests could never have been of any practical service. The position would have been like trying to do intelligence testing with a single test battery which passed all subjects of intelligence quotient above 70 and failed the remainder. The higher group would be viewed as "normal" and the lower group as "defective". The variations within the "normal" group would be so great that such a test would be almost useless, but in colour vision the variations within the "normal" group are so small that such a method has been of considerable practical service.

The problems of colour-vision testing never could be compared adequately with those of intelligence testing, however, because mental age increases with chronological age during childhood and to a less extent in adolescence, whereas colour-vision sensitivity seems to be little if at all affected by age. In intelligence testing, broadly there is only one kind of defect of outstanding interest, though there

is a small amount of variation in relative degree of mathematical, verbal and spatial ability, while in colour vision there are six distinct forms of major defect, not to mention small variations in the bulk of the population which occur in four different ways.

While the gap in sensitivity variations has made crude testing for colour blindness easy, it has made thorough testing difficult. Those tests which separate the major defectives from the bulk of the population are far too easy for normal subjects, and do not distinguish between variations among them. The same tests are far too difficult for the major defectives and fail just as completely to separate their sub-classes effectively. A certain number of subjects are indecisively placed, but these are not necessarily the true intermediates. In addition, the tests could not show us between exactly what extremes they were intermediate, because there are several extremes, none of which is clearly distinguished from the others by these tests.

It is therefore necessary to have a test for the major defective group which will separate them effectively into their sub-classes. There must also be a test which will do the very same thing for the bulk of the population, who are not major defectives. The normal group are highly sensitive and vary little among themselves, whereas the colour blind are highly insensitive and vary much. Unless the same test could be applied to all groups, there would be no way of making a direct comparison between them, but to make a single test battery which would do this has been a technical problem which has caused experimental psychologists great difficulty. For the normal group it calls for an adequate psycho-physical technique for sensitive threshold measurements. The same test must be applicable in a sufficiently flexible way to suit the most extreme defectives. To the best of the writer's knowledge these peculiar problems have never been solved before, and this is the main reason why there is so much confusion about the nature and relative magnitude of colour-vision defects.

A further difficulty is due to the special nature of colour-vision defects themselves. A simple threshold test for ability to distinguish a given hue from grey of equal brightness, in terms of saturation, does not work. Its failure is due to three simple facts : (1) That diminished sensitivity to certain colours, red and green, does not make them less and less distinguishable from neutral grey, but they usually become more and more yellowish; (2) That variations in red and green tend to occur in two forms, (a) of increasing difficulty in distinguishing them from a standard yellow, and (b) of great changes in the balance between them; and (3) That the same two modes of

variation are also found in the yellow-blue pair, but the standard to which they approximate as they weaken is now grey and not yellow.

Several forms of simple threshold test for colour were tried out with the colorimeter or anomaloscope. One of these involved measuring the thresholds for the discrimination of red, orange, yellow, yellow-green, green, blue-green, blue, violet and purple from greys of equal brightness. In another form of the test red, orange, yellow-green and green were tested in comparison with a yellow standard of equal brightness, while yellow, blue-green, blue and violet were compared with a standard grey. These tests failed to discriminate the colour weak from the major red-green defectives, and were therefore abandoned, after being applied to preliminary groups of subjects.

There is another and more narrowly psycho-physical difficulty in the way of simple threshold tests for colour sensitivity. The gradations between neutral grey and any given hue in terms of saturation are very fine, as also are the gradations between such hues as red, yellow, yellow-green and green and a standard yellow. Anybody who has seriously studied threshold measurements will know that numerous repetitions are necessary before a reliable mean value can be obtained. With major defective subjects the margin of uncertainty is increased greatly. For practical testing it would be unduly laborious and fatiguing to carry out threshold tests of this kind. The method of desaturating a hue with its opposite or complementary, which has been employed throughout this research, utilises far more decisive saturation changes. This method also reveals natural differences of colour sensitivity where the simple threshold technique would fail. Therefore the tests are within the bounds of practicability. All these points about the nature of the variations of sensitivity to be tested and the technique of testing them can be explained clearly at this stage, but only because the experiments previously described have been carried out. The writer did not know beforehand what complications would have to be faced.

Further difficulties of colour-vision testing may be described as " clinical ". Normal, deviant and colour-weak subjects, who form the bulk of the population, seldom present any difficulty to the tester. In dealing with the colour weak there is the possible danger of giving them the benefit of the doubt, or of allowing them to learn how to do the tests by secondary cues in the course of repeated attempts. For these reasons it is recommended that the test should be as short as compatible with a reliable result. However kind the examiner wishes to be, he is advised to take the worst rather than the best

performance if there is any doubt. Nevertheless it is impossible to lay down any perfectly rigid rules in this matter, and only experience will give the necessary guidance. It is not recommended as a valid principle of mental testing in general to take the worst rather than the best performance as typical. This principle applies to colour-vision testing because of the peculiar condition to be faced, namely the ease with which the subject may learn to do the test by guides or cues external to the capacities being tested. This is so well known to colour-vision testers and has been mentioned so often in the past that it need not be stressed again. Whether it is a principle applicable in any other fields of testing depends upon the particular concrete problems to be faced in each field, and on the special manner of standardisation of the test which is being used.

In addition there is another point of difference between colour-vision testing and, for example, intelligence testing. Our interest in weaknesses and defects of colour vision almost invariably centres about the problem whether a subject might make a certain degree or kind of error, and it is more important to us to know the worst rather than the best performance of which he is capable. This will always be necessary while life depends on the use of colour signals. In intelligence testing we wish to know the best of which he is capable.

The major red-green defectives present many clinical problems to the tester. Often they are experts at hiding their defects. No subject may be allowed to avoid being tested on any pretext, however plausible. The more he presses his excuses the more suspicious we become. One red-green blind man always had a train to catch when invited to do the test. If not asked to be tested, however, he was ready enough to have a chat over a cup of coffee. In the actual test situation, persistent doubts or unusual difficulties in agreeing that two hues might be alike, or problems arising from claims of quite exceptional sensitivity, are always to be viewed with suspicion. Here again, nothing but experience can guide the tester, because some normal people are obstinately particular and will never agree that two spots of colour are alike. If excessive caution is shown by the subject over a normal colour match, he is under suspicion, whereas if he uses excessive caution in making a peculiar match, then he is almost certainly abnormal. The difficulty will then be to decide the exact nature and extent of his abnormality, but experience shows that this is usually greater rather than less than either the subject or the tester is likely to suppose. Hence it is better to err on the side of an over-estimate than an under-estimate of the defect. Since we have to

deal with human individuals, it is quite impossible that colour-vision testing will ever be reduced to terms of a purely mechanical science. Those who are not good clinical workers will never be good testers.

A proportion of major red-green defectives appear to have what might be described as fluctuating sensitivity. This was described clearly by a protanope who was tested while this section was being written. He said that he was usually unable to distinguish a red object on a green background, such as a golf tee in the grass, unless it was pointed out to him. Then he was able to see it clearly as red. Similarly if a red figure on a green background in the Ishihara Test were outlined with the back end of a pencil he became aware of it, but it soon faded again from his vision. Fluctuations of sensitivity lead to some confusions in testing, because the subject will sometimes make correct judgments of the hues of the spots of light in the colorimeter, and sometimes he will fail surprisingly. In these cases it is only safe to take the extremest range within which gross errors occur as the measurement of the subject's defect. If colour blindness were not a dangerous defect it might be possible to take a more lenient view, but there are two serious objections to this: (a) that those with fluctuating colour blindness are in fact the most dangerous, because it is possible for them to appear sometimes as if normal; (b) that these subjects, like the anomalous and the moderately red-green blind, are definitely among the sex-linked defectives, and there is no scientific justification for confusing them with the normal population.

Finally, it must be said that those who " dodge " are not all conscious or intentional dodgers, and many children are experts at unintentional dodging. Only an exceptionally objective-minded and self-critical protanope, or one who had an unusual impulse to make an exhibition of himself, would be ready to agree that pillar-boxes might be called " black " just as well as " red ". With experience one learns many of the unintentional dodges which people tend to use in their efforts at self-protection. The writer was correct in his surmise that a boy, whose mother said that he had been brought up in the country and had not the same opportunities as other boys to learn the names of colours like violet, magenta and some kinds of green, would be a deuteranope. No mother would think of saying such a thing about her son unless he had made some errors which other people had also noticed, and the colours she named were among those which a deuteranope often finds difficult to distinguish.

OBJECTIONS TO GROUP TESTING

Unless better methods than any in use at present are found there is no hope for group testing of colour vision. Attention may be directed to the three outstanding objections to group testing, because many people who feel that it would be a great advantage do not fully realise the difficulties which it encounters.

(1) No test of colour sensitivity has been made which is equally discriminating from different angles or directions of vision, or at different distances. The reasons for this are purely physical. If we use large pseudo-isochromatic plates, like the excellent plates of the Collins-Drever Group Test, then it will be impossible to arrange for the projected areas on the retinae of all the subjects tested to be the same. More important than that, for some testees the projected area of the test plate will be wholly within and for others it will partly overlap the fovea. Since there is an important class of red-green blind subjects whose colour vision is better outside than inside the fovea, this is a serious matter. All colour-vision tests must be limited to foveal stimulation. Quite apart from this problem, however, the ease of a test of colour vision is proportional to the size of the area of the retina stimulated, other things being equal, and those who are near a group test must have an advantage whatever type of test is employed. If the group of subjects is arranged in a semi-circle, so that all are at the same distance from the test, there are still difficulties owing to the change in projected shapes of the test spots or objects due to perspective. There are also differences owing to the varying intensities of light reflected at different angles if pseudo-isochromatic plates are used, and, since some inks shine more at certain angles than other inks, figures invisible from immediately in front may be clear from one side but not from the other. It is comparatively easy to gain help in doing the Ishihara Test, even as an individual test, by tilting the plates until some of the figures can be read by the varying intensity of the light reflected at different angles. Many colour-blind subjects habitually use this dodge and must be checked from tilting the plates or moving the head from side to side. If the colorimeter is used there is a further difficulty, though the problem of reflection is overcome. It is easily shown that red (or yellow) light is less scattered in the diffusing screen than green (or blue). Hence the scale reading for a red-green (or yellow-blue) mixture which matches a given standard will vary with the angle from which the testee views the spots of light.

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In one experiment the writer tried projecting the colorimeter test spots upon a reflecting wall, with a suitable magnifying lens system, after removal of the milk glass plate. Although this allows a group of subjects to view these enlarged spots, all the problems of perspective and distance are introduced again, in addition to those of the greater scatter of blue and green than of red and yellow rays by the reflecting surface. It might be thought that all these physical difficulties were not weighty objections, but experience has led to the conclusion that they are far too serious to allow the development of group testing unless they are fully overcome.

(2) Experience with the Collins-Drever Group Test has shown that those who escape in a group owing to the varying physical conditions described above are not necessarily the least defective. They may be those who are most skilful (intentionally or otherwise) in evading detection. After one or two experiences of re-testing individually the members of a group who had been given a group test it was abandoned altogether. In one class of about forty students one deuteranope was found with the Collins-Drever Group Test, and afterwards one extreme protanope, a second deuteranope and a red anomalous man were found in individual tests with the colorimeter. The fault certainly does not lie in the construction of the Collins-Drever Test itself, which is excellent if used with strict precautions as an individual test at a sufficient distance to be viewed in foveal vision. The difficulties are inherent in the physical conditions described above.

(3) In a group, especially of children, it is impossible to be sure that none receives guidance (intentional or unintentional) from others. Since many major defectives, even among children, are masters at unintentionally exploiting guidance which is unwittingly given, this is very important. However much reliance may be placed upon their good faith, the tendency of red-green defectives to take advantage of all manner of secondary cues and indications cannot be overlooked. It is to them just as spontaneous as the use of secondary cues in the perception of size, shape and distance to the ordinary person.

REVIEW OF THE EXPERIMENTS

Seven series of experiments on colour vision were carried out during more than eight years, with a view to revealing the nature of the variations of colour vision to be dealt with, measuring them and devising a satisfactory test which could be expected to have practical and theoretical applications. These experiments have been described

in detail in the previous chapters, and the remainder of this chapter will be devoted to summarising their results and stating the general conclusions to be drawn from them. In the first place a short review of the experiments will be given.

The first experiment was carried out on 103 men and 98 women who were normal, deviant or colour weak, and upon 14 men and 5 women who were major red-green defectives. One yellow-blue blind man was included. This experiment was carried out with two pairs of rotating disks made up of Hering's coloured papers. The first pair consisted of one disk of red and green, and the other of yellow, black and white. The second pair consisted of one disk of yellow and blue, and the other of black and white with a small sector of green. The proportions of red and green required to match a suitably desaturated yellow were measured, together with the brightness levels of the yellow for all matches and all subjects. It was found, as explained before, that subjects varied both in the difference between their average mixture of red and green and the average mixture of the whole population, and also in the range of mixtures of red and green which would match the yellow. These two measurements have been called " deviation " and " matching range ", and they proved to be of fundamental importance. Similar measurements were made with the second pair of rotating disks, and these gave the deviations and matching ranges for the comparison between a neutral grey and a mixture of yellow and blue.

It was found that the subjects could be classified as " deviants " if their red-green or yellow-blue deviations were more than 1 × sigma, and as " extreme deviants " if more than 2 × sigma, while the anomalous were much more extreme. At a later stage the distinction between deviants and extreme deviants was given up, and the term deviant was applied to those subjects who had deviations of more than 1 × sigma and were not anomalous or colour blind. Those with matching ranges two or more times the modal range were classified as " colour weak ", but the weaknesses of the colour blind, though similar in character, were much more extreme. About 20% of the subjects were deviant, colour weak or both, and there were about 5% of colour blind and 2% of red and green anomalous men on this system of classification.

Correlations between red and green and between yellow and blue weaknesses were negative, while other intercorrelations for colour sensitivities and for brightness levels of corresponding colours were small. There was no correlation between colour weakness and deviation, even among major defectives. Brightness level was

largely independent of variations of colour sensitivity. There was no tendency for anomalous or red-green blind subjects to be weak in yellow or blue. The red-green blind were found to be clearly divisible into two classes—protanopes, with darkened red, and deuteranopes, for whom red is not darkened. Both types are red-green blind and both are variable in degree of defect, but the anomalous were found to be distinct from the moderately red-green blind. The errors of naming and the colour confusions of all these defectives were found to be logical and understandable on the basis of their measured defects.

After the completion of this experiment it was decided to make a simple anomaloscope or colorimeter for the use of colour filters instead of paper disks. The instrument was carefully designed to fulfil the requirements shown to be necessary by the rotating disks experiment, and all the remaining experiments reported in this book were carried out with it.

Three preliminary experiments were then carried out in order to discover the best technique and colour filters to use and to determine the degree of efficiency of the anomaloscope. The first employed two paired colour filters, each made in two halves. In one pair the halves were red and green and in the other pair they were yellow and blue. Thus the yellow standard for the red-green experiment and the grey standard for the yellow-blue experiment were made from filters identical with those in the variable stimuli. A special technique was worked out for this test. It was carried out upon 51 women and 43 men who were normal, deviant or colour weak, and 7 men who included 1 protanope, 5 deuteranopes and one who was green anomalous.

This test broadly confirmed the results of the rotating disks test, but it was unsatisfactory because it tended to magnify the errors of measurement by giving the subjects too much liberty of choice; because it failed to discriminate efficiently between anomalous and deviant subjects; because it did not employ monochromatic filters; and because it made measurements of brightness level quite unnecessarily difficult. It was therefore abandoned, though it had the advantages of quickness, simplicity and the use of spots of light so bright that it could be carried out in a room lighted with diffused daylight.

The next two preliminary experiments were carried out on a small group of subjects, namely 22 men and 12 women who were not major defectives, 1 green anomalous man, 5 protanopes and 2 deuteranopes. The " Spectrum Filters " test employed the

Ilford spectrum red, green, yellow and blue filters. It duplicated the conditions of the rotating disks test, except that monochromatic filters replaced the Hering papers. In the " Micro Filters " test another attempt was made to devise a simplified technique. It used four polychromatic filters, three of which belonged to the Ilford " Micro " series. Two were red and green and the other two were yellow and blue, and all four were chosen so that the red-green mixture could be matched against the yellow-blue mixture when certain proportions were used. A special technique was devised for this test, and although in principle it was very simple, in practice it proved even more confusing and indecisive than the Paired Filters test. It was therefore abandoned, and the Spectrum Filters test was satisfactorily incorporated into the next experiment.

The fifth experiment was carried out with two sub-tests based on the Spectrum Filters test, and three sub-tests added, namely orange with blue-green, yellow-green with violet and purple with green, using monochromatic filters with the exception of purple. The main aim of this experiment was to find out whether variability of colour sensitivities was equally spread over all nine colours, red, orange, yellow, yellow-green, green, blue-green, blue, violet and purple, or whether it was mainly confined to red, yellow, green and blue. The experiment was carried out upon 103 men and 106 women who were normal or minor defectives, 20 red-green blind, 9 green anomalous and 3 red anomalous men, and upon 3 red-green blind and 2 green anomalous women.

The proportions of deviant and colour-weak subjects were found to be about the same as in previous experiments. Most of these subjects had shown some weaknesses of colour vision in daily life. It was shown by general inspection of the results, and confirmed by factorial analysis, that the variations of colour sensitivity were confined to red, yellow, green and blue, in the sense that no weaknesses existed in any of the intermediates in any subject which were not found to a greater degree at the same time in one or more of the four primaries. About 3% of men and women were found to have the violet end of the spectrum markedly darkened. Details about the major red-green defectives confirmed the results of previous tests, except that three red anomalous men were found, in one of whom the red end of the spectrum was not darkened.

It seemed to many critics that the negative correlations between pairs of colours measured together, such as red and green, might have been produced by the technique of the experiments. Hence a sixth experiment was set up in which colours were desaturated

with their neighbours, and in which intermediates were used as standards. This experiment had four sub-tests, red-yellow, yellow-green, green-blue and blue-red. It was carried out upon 62 normal and minor defective subjects, 2 deuteranopes, 1 protanope, 4 green anomalous subjects, one of whom was a woman, and 2 red anomalous men.

The results of this test were factorised, and showed that the first bipolar factor contrasted red against green and yellow against blue at the same time, while the second and smaller bipolar contrasted colours measured by desaturating each other. The experiment therefore showed that the negative correlations were mainly between red and green and between yellow and blue, while subsidiary negative relationships were produced by the technique of the experiment. This was called the "Intermediates Experiment", and it showed that the confusion of blue-green with green is the most frequent type of colour-vision error in daily life, and is due to blue weaknesses and not to mere errors of naming.

THE FOUR-COLOUR TEST

When it was found that there were no defects of colour vision in orange, yellow-green, blue-green, violet or purple, which could not be measured better by testing red, yellow, green or blue, a simple test of these four colours was devised. It was based upon the "Spectrum Filters" test just described, but certain alterations were made to improve it. This Four-Colour Test was then carried out upon about 330 men and 260 women who were normal or minor defectives, upon 26 protanopes, 41 deuteranopes, 3 of whom were women, 42 green anomalous subjects, 9 of whom were women, and 11 red anomalous subjects of whom two were women. The proportions of major defectives will be discussed in a later paragraph. The test confirmed results from previous experiments, and showed that a simple and efficient test of colour vision could be made in this form. The correlations in a re-test of about 35 subjects were over ·9 for red and green and over ·6 for yellow and blue.

The colour vision of all subjects showing any abnormalities was studied with great care, and most of them were given other tests such as the Ishihara, Holmgren Wools or Beads. The deviations of the normal group conformed well to a normal distribution, and it seemed satisfactory to class those with deviations of about 2 × sigma or more as "deviants" because almost all of them showed slight weaknesses in daily life. About 11% of men and 20% of women

had matching ranges of two or more times the modal range in red and green, and about 15% of both sexes in yellow and blue, and these subjects were reasonably classed as red-green or yellow-blue weak accordingly.

The experiment showed that protanopes are more often extreme and deuteranopes more often moderate, and that red and green anomalous subjects are distinct from the moderately red-green blind and form consistent groups among themselves. About one half of the red anomalous subjects had red of normal brightness. It was suggested that there is a small class of major defectives who have exceptional fatiguability rather than anomalous colour vision or colour blindness. Comparison of the results of this and of the Ishihara Test showed that the Ishihara is reliable for rejecting all major red-green defectives, but has a very ragged " cut-out " and fails to discriminate effectively between the sub-classes of major defectives or between normal, deviant and colour-weak subjects. In this respect the Four-Colour Test fully confirmed the Rotating Disks Test.

The Four-Colour Test has the advantages of cheapness and ease of construction, quickness and simplicity of application, efficiency in distinguishing between normal, deviant and colour weak, and between red and green anomalous and the two classes of red-green blind subjects, and it gives a measurement of the degree of defect of the colour blind on the same scale that it applies to the normal. It is a simple psychological test, which compares individuals with standardised norms for the population, and therefore opens up many possibilities for industrial and scientific research upon colour vision. It may be open to many improvements, but forms a possible basis for an efficient science of colour-vision testing. It is portable, can be set up in any dark room, and is independent of colour naming, although naming of colours is taken into account as a subsidiary part of the test routine.

NORMAL, DEVIANT AND COLOUR-WEAK SUBJECTS

It is clear from what has been said in this and previous chapters that we may divide the population into two general classes for colour vision : (a) normal, deviant and colour weak, (b) colour blind and anomalous. The characteristics of all these kinds of subjects have been dealt with in detail, and in this section the reader will be reminded of the main points previously explained. First of all we may describe the ordinary deviant and colour-weak subjects as minor defectives, in contrast to the group of colour blind and

anomalous subjects who are major (sex-linked) defectives. It is an open question whether exceptional fatiguability must be classed as a major or as a minor defect. The detection of this condition among the major defectives who are already extremely weak in certain ways would be difficult, because it would have to be distinguished clearly from their other defects. In the normals and minor defectives it is comparatively easy to detect, and has therefore been classed as a minor defect. If convincing evidence were forthcoming that it was sex-linked, then it would have to be re-classified as a major defect. It is not a general characteristic of the anomalous.[37]

The definition of minor defects, apart from extreme fatiguability, is (a) statistical and (b) based upon observations of colour vision in daily life and performance in common colour-vision tests. In dealing with minor defects in this research the aim has been to pick out with the colorimeter those subjects who lie at the extremes of the distributions for deviation and matching range, and to study their colour vision in any other ways possible in order to find out the levels at which it is justifiable to call them deviant and/or colour weak. After the Rotating Disks Experiment the data seemed to indicate that for colour weakness a suitable criterion would be two or more times the modal matching range in the pair of colours in question, excluding the colour blind who are much more extreme. The mode had to be used rather than the standard deviation, because the measurements are strongly skewed. This criterion cannot be taken as absolute, but would have to be varied somewhat in accordance with the requirements of testing in particular situations. For example, in the dyeing trade it might be necessary to take 1·5 times the modal range, and in colour printing 2·5 times the mode might suffice, or vice versa. Twice the mode, however, corresponded with the tendency to make slight errors in daily life and to have some difficulty with other tests, and also it sufficed to pick out the expected proportion of normal heterozygotes among women. Therefore it seemed to be a good criterion, and if three times the mode were taken a very small proportion of sex-linked defectives would be included unintentionally.

The deviations are distributed in a normal curve, and for them sigma scores were used. The data indicated that those subjects within the limits of $\pm 1 \times$ sigma should be classed as perfectly normal, those between ± 1 and $\pm 2 \times$ sigma and those beyond these limits (excluding the anomalous, who are much more extreme) as "deviants". This classification, like that for colour weakness, is not absolute, but must depend on circumstances, though deviants

on this system seemed to be the ones who tended to make slight errors in daily life.

There is no correlation between deviation and colour weakness, and both criteria must be taken into account in assessing the colour sensitivity of all minor defectives. A combined criterion might have been used, the measurement taken from the appropriate end of the colorimeter scale (as a zero) to the point of just noticeable difference between the colour in question and the standard. This criterion was not employed, however, because it overlooks the important distinction between deviation and colour weakness, and is more difficult to handle.

There are no special advantages in the scale of sigma scores, except that the expected number of subjects in any group can be calculated from the normal curve. I should like to offer a serious warning against using sigma scores as equivalent measurements in different tests. Experience showed that a characteristic green anomalous subject, who had been tested repeatedly and acted as a criterion for comparing the efficiency of different tests, was not distinguishable from the green deviant subjects in one test, whereas a more efficient test gave him a deviation of about 7 × sigma, like other green anomalous subjects. The use of sigma scores to equate the results of these tests and to exploit them for further calculations would have been most unscientific. The performance of a subject depends on the transmission bands of the filters or on the reflection bands of the papers used, and on the efficiency of the psycho-physical technique. Sigma scores do not equate different colour filters or correct techniques which are at fault. The use of sigma scores for combining the results of different tests may be dangerous in all psycho-metrics, but in colour vision we have objective external criteria to guide us in rejecting it.

In general the study of minor colour-vision defects showed that the colour naming errors of people who are not major defectives are due to and can be explained by their defects, and are not simply the results of erroneous learning of colour names. This was shown most clearly in the commonly found tendency to confuse desaturated blue-greens with green, which is characteristic of people with minor blue defects. It is easily understandable, because the reduction in sensitivity to blue leads to a breakdown of the distinction between blue-green and green, so that the same name tends to be applied to both, and, since the person is more certain of greens, for which there is no weakness, he tends to use the term green rather than blue in cases of doubt. A very interesting example was found in a family

in which a girl with exceptional blue deviation called blue-green and blue " green ", violet " blue " and purple " violet ". She was a dominating and assertive person, and her younger sister was submissive in comparison, and, although she had no blue defect, the sister had learned to use the terminology of the defective girl. The submissive sister easily proved that she could clearly distinguish blue, blue-green and green, while her elder sister had great difficulty. Similar peculiarities of naming were also found where there was a minor defect in one of the other primaries, and they were always understandable on the principle that the weak colour was subtracted from a mixture of the pair which were confused.

ANOMALOUS SUBJECTS

Throughout this book the terms " red anomalous " and " green anomalous " have been used in place of terms like " anomalous trichromat ", " protanomalous " and " deuteranomalous ". There are no yellow or blue anomalous subjects because the curve of distributions of yellow and blue deviations is extended to include the extremes. The problem of terminology for anomalous subjects is complex, and is not made any simpler by the frequent use of the expression " anomalous colour vision " for any major red-green defect by ophthalmologists who wish for very good reasons to avoid any expression in which the word " blindness " occurs. For obvious clinical reasons it is unwise to suggest to a person, even indirectly, that he has " blindness " in any sense, and indeed if in colour-vision testing we do use the expression " colour blindness " to the subject, it is very wise to point out to him that this is merely a convenient expression used conventionally for certain peculiarities of colour vision and does not mean that he is blind. According to the usage of the supporters of the Young-Helmholtz theory, those subjects will be called " anomalous trichromats " whose colour vision has a marked red or green weakness, but who still require three primaries to match all spectral hues. This usage fails completely to distinguish the deviants and colour weak, whose defects are not sex-linked, from the truly anomalous, and it fails in turn to distinguish these from the moderate protanopes and deuteranopes. Indeed, few subjects are so extreme in red-green weaknesses that they are completely dichromatic, and in consequence on this system we might well use the term anomalous of all major red-green defectives, like the ophthalmologists, but for a different reason. If that were done a new term would have to be invented for those subjects

who are truly anomalous in the sense defined in this research, and there would be a senseless multiplication of terms. The writer has considered the possibility of trying to settle the confusion by inventing new terms, but it seems that the multiplication of terms in science is a nuisance, and it is better to use terms as nearly as possible in their conventional senses, but to define them accurately, rather than to invent new words for what are in fact old ideas. Houstoun's term " colour different "[2] has much to recommend it in place of the terms " red " and " green anomalous ", on the ground of common sense, but as defined by him it is unfortunately no clearer than the other terms mentioned above, and if we did adopt it we should be driven to speak of " red different " and " green different " subjects. An overwhelming objection to the term " protanomalous " is that it suggests darkened red owing to its connection with " protanope ", whereas one half of the red anomalous subjects have red of normal brightness. The writer does not mind what terms are used provided the true distinctions between the various classes of defectives are recognised.

After considerable thought it has therefore seemed best to use the term " anomalous " of those subjects who have a major and sex-linked red-green abnormality which takes the form of an extreme deviation (6 × sigma or more) towards the red or green side without a marked increase in matching range. These are then sub-divided into the red and green anomalous, and the red anomalous are divided into those with and those without darkened red. The red-green blind are those with an extreme increase of matching range in red and green, but not necessarily with an increase of deviation.

Anomalous subjects are clearly distinguishable from the red-green blind, and are not simply the least defective of the colour blind, some of whom are indeed less defective than the anomalous. There is, however, a small proportion of intermediates between the anomalous and the least defective of the red-green blind on the one hand, and the most extreme of the deviants on the other. The distributions of these classes of defectives are statistically distinct.

The anomalous subjects often fail altogether to notice their defects in daily life, though they sometimes report difficulty in distingushing shades of green or of red according to the nature of their defects. They are outright failures on the Ishihara Test, which does not distinguish them from the least defective of the red-green blind. They are definitely unsafe for work with coloured signal lights. Their frequencies in the population will be discussed later. They are certainly " trichromats " in the sense of the three-colour theory,

but their peculiarity lies in having a scale of colour mixture values different from that of the normal in a striking and definite way, rather than in having to use too many names for the hues they see, like the red-green blind.

RED-GREEN BLIND SUBJECTS

The colour-blind subjects are to be distinguished by having a reduction, rather than a difference in scale, of sensitivities to colour. It is necessary to touch upon the possibility of yellow-blue blindness. Those subjects with very large matching ranges in yellow and blue are the extremes of the continuous variations of yellow-blue sensitivity, whereas the red-green blind are separate groups discontinuous from the normal and colour weak. Nevertheless, if a subject with extreme yellow-blue weakness is found, his difficulty will be that of adapting too many colour names to the hues he sees, like that of the red-green blind, but in the realm of blue and yellow. He will, for instance, tend to apply the same names to blue, blue-green and green, and perhaps gain the reputation of being a person who asserts that there is no real difference between blue and green. It is not unreasonable, with these precautions, to apply the term yellow-blue blind to the most extreme of the yellow-blue weak series, but on the whole it is better avoided.

The red-green blind are clearly divided into two classes : protanopes and deuteranopes. Protanopes have the red end of the spectrum greatly darkened, and have in consequence been called " red blind ", while the deuteranopes have been called " green blind " for no very good reason. These terms lead to confusion, because both types are red-green blind and tend to confuse reds, fawns, browns and greens of equal brightness for them. Rivers tried to introduce the terms " scoterythrous " and " photerythrous ", which are very tempting, but it seems easier to follow the familiar terminology. If the reader chooses to use the terms " scoterythrous " for protanope, " photerythrous " for deuteranope, "red different" for red anomalous and " green different " for green anomalous, the writer will make no objection. The term " tritanope ", however, which was introduced on the assumption that there must be a third kind of colour blindness which was due to the absence or weakness of the blue (or third) receptor of the Young-Helmholtz theory, is more objectionable. It does not correspond to any distinct type of defect which can be observed, and must be replaced by the terms " yellow " and " blue " deviant and " yellow-blue weak ".

Protanopes and deuteranopes are closely comparable except that in protanopes there is a great reduction in sensitivity to the red end of the spectrum. This affects orange less than red and yellow hardly at all. Protanopes and deuteranopes are both variable classes, but they do not overlap. Most protanopes are very poor at seeing anything but black where there is red, but when they do see it they tend to confuse red with dark oranges, browns, and greens. There is a proportion of moderate protanopes, but their weakness in red and green is not correlated with the degree of darkening of the red end of the spectrum. On the other hand, although there is a fair proportion of deuteranopes who cannot distinguish reds, oranges, fawns and greens of equal brightness, the majority are able to see reds and greens as distinct hues if sufficiently saturated. A very small number of red-green blind subjects are not much more defective, in terms of colorimeter measurements, than the few most extreme of the colour weak. Some red-green blind subjects who are moderately defective tend to confuse red and green even when they can distinguish both from yellow. It is as if there were three possibilities : (a) that red, yellow and green might be equal in hue and saturation; (b) that red might be the most saturated and green the least saturated of the three, although they were equal in hue; (c) that both red and green, although equal in hue, might be more saturated than yellow. The first condition would correspond to the inability to distinguish red, yellow and green; the second condition to the ability to learn to distinguish them by saturation, with much difficulty; and the third to the peculiarity just mentioned, in which both are distinguishable with difficulty from yellow but not at all from each other. This is one reason why a test for colour blindness must include naming of hues, though it must on no account depend on naming alone.

Red-green blind subjects vary in deviation as well as in matching range, but it is in the majority of cases easy to distinguish them from the anomalous. Their deviations are seldom as great as those which are characteristic of the anomalous; their matching ranges are much larger; they generally accept the mid-matching point of normal subjects, while it is unhesitatingly rejected by the anomalous. No evidence has been found that increase of simultaneous contrast is characteristic of either red-green blind or anomalous subjects. The supposed evidence for this has been the result of failure to realise that red-green defectives may apply colour names (satisfactorily for them) to greys which are only very faintly coloured for us, or even quite colourless. They do this not because they can see more

colour in these hues by exaggerated simultaneous contrast than normal subjects, but because they see very much less colour in many saturated hues than the normal and can apply colour names to greyish hues which are just as saturated for them. The main confusions of the deuteranope are between reds, oranges, fawns, and greens, while magentas and purples tend to look grey to them and may be confused with green. The main confusions of the protanope are between reds, dark browns and blacks, and between greens and fawns, while for them purples and magentas tend to be confused with pale blue because the red is subtracted.

Since the distributions of measurements of the defects of anomalous and red-green blind subjects are not continuous with the corresponding measurements for normal subjects, all major defectives must be regarded as very abnormal. There can be no question of thinking of the less defective among them as " almost normal ", or of taking a lenient view of their defects so long as green-orange-red signal systems are in general use.

ORDINARY AND DEVIANT DEUTERANOPES

A proportion of the deuteranopes, though not necessarily the least defective of them, have extreme green deviations. These tend to form a fairly well defined class with average deviations of about $5 \times$ sigma and should be considered as a group discontinuous with the other deuteranopes. A distinction will be drawn, therefore, between " deviant " and " ordinary " deuteranopes, and, although the rotating disks and earlier tests did not separate these two groups so clearly as the four-colour test, it has been possible to give the relative frequencies, and these are shown in Table 116. It will

TABLE 116

PROPORTIONS OF NORMAL AND DEVIANT DEUTERANOPES IN ALL THE TESTS

	Ordinary Deuteranopes	Deviant Deuteranopes	Totals
MEN ..	36	25	61
WOMEN ..	1	5	6
TOTALS ..	37	30	67

be understood, with a moment's reflection, that a deviant deuteranope never has so large a matching range as the most extreme of the ordinary deuteranopes, but may have a matching range larger than that of some of them. If the matching ranges are alike, then the deviant

deuteranope has the added weakness of his extreme deviation and is the more defective of the two. The extreme deviation of these subjects is hereditary. They are the " anomalous deuteranopes " mentioned by de Vries;[3] Willmer has found two classes of deuteranopes which are probably the same two groups.

BEARING OF THE RESULTS ON COLOUR-VISION THEORIES

If we take the principal theories of colour vision as hypotheses to be tested by the experiments, then it would seem that the facts can be explained by a theory involving four primary sensations for hue and one for brightness, while less than this number of primaries would be insufficient. In this respect the results of all the experiments are consistent and decisive. Expressed in the briefest possible way, this means that the most sensitive colour vision which has been studied could be accounted for in terms of four primaries for hue and one for brightness, while no variations or abnormalities of colour vision have been found which could not be explained with the same framework of primary sensations. This may be explained more fully.

The evidence that people with normal colour vision are strictly trichromatic is not convincing. Even if the problem of brightness were omitted, four primaries for hue would be required to account for the " negative " stimuli needed in three-colour mixing experiments. Those who use the examples of three-colour printing and three-colour photography to support corresponding theories of colour vision tend to forget that two-colour printing and photography are frequent, while the more colours added above three, within practicable limits, the better the result. Three is neither the smallest possible nor the best number which can be used in these processes. It is simply the smallest number with which a reasonably satisfactory result can be obtained. The majority of pieces of apparatus used to demonstrate three-colour mixing, like three-colour printing and photography, in fact use all the wave lengths in the spectrum, because they do not employ monochromatic lights, and they do not really provide any evidence at all in favour of the three-colour theory of colour vision. It is well known that all the hues of the spectrum cannot be matched exactly in hue and saturation by the use of no more than three monochromatic primaries, unless "negative" forms of these primaries are also introduced. These "negatives" are in fact additional primaries, "positive" in the hues they are used to desaturate.

When we come to study the variations of normal colour vision

we find that there is strong evidence that red, yellow, green and blue are the sensitivities which vary and this indicates that they are the primaries for which we are searching. If yellow did not vary independently of red and green, it could be omitted from this list of primaries, but it does vary independently and must be included. This confirms the evidence from introspective analysis, that yellow is a sensation of unique and irreducible quality, and evidence from binocular colour combination experiments, that yellow cannot be matched except with great difficulty in binocular mixtures of red and green.[4]

When we study the extreme variations of colour sensitivity we still find that they affect red and green independently of yellow and blue, and that yellow sensitivity may be perfectly normal in the red-green blind. This could not possibly occur if red, yellow and green sensations were related in the ways suggested by the Young-Helmholtz theory. Furthermore, red, yellow, green and blue are the sensitivities which undergo primary variability, and not orange-red, yellow-green, and violet-blue, as the Young-Helmholtz theory would require.

The analysis of the types of variability makes the position even more convincing. Red variations are negatively correlated with green, and yellow with blue, when adequately tested, and there is strong evidence that these negatives are not produced by the techniques of the tests used. This means that red and green on the one hand, and yellow and blue on the other, are alternatives in the sense that red varies at the expense of green and yellow at the expense of blue and *vice versa*. Such a mode of relationship is not provided for on any colour-vision theory but that of Hering and its modified form due to Houstoun. At the same time there is also a tendency for the members of these pairs to vary together, and a major distinction between types of defect is due to this : where red and green or yellow and blue vary together we have the tendency for colour weakness; where they vary inversely we have the tendency towards deviation defects. Extreme forms of variation of red and green together give rise to red-green blindness; extreme forms of variation of these colours as alternatives give rise to anomalous colour vision. Houstoun foresaw these facts and suggested that they could be explained on the hypothesis of red-green and yellow-blue cones which had two modes or frequencies of response, one corresponding to red (or yellow) and the other to green (or blue). Another form of the hypothesis would suggest four different kinds of cones, acting in pairs, one as an alternative to the other in each pair, and this will be mentioned below. Houstoun, however, pointed out

that where the point of average change-over from one mode of response to the other with changing stimulus varied, but the cones still changed almost all together, we should find colour vision which has been called anomalous. Smaller variations of the same kind would give rise to ordinary deviations. Where the average point of change-over is not greatly affected, but where the cones tend to change in a scattered manner, instead of changing all together, or almost so, we shall find weaknesses of red-green or of yellow-blue discrimination, of which red-green blindness is the most extreme form. In the group of deviant or anomalous deuteranopes, mentioned previously, both types of abnormality occur together.

If it is too improbable that these alternative types of response are able to occur in the same cones, the theory may be modified to include the supposition that there are two pairs of cones, red and green responding cones in one pair and yellow and blue responding cones in the other pair. The applicability of the theory is unaffected by this modification, because deviations and anomalous colour vision are now produced by variations either in the relative numbers of cones of the two types present in the appropriate pair, or by variations in the readiness of their tendencies to respond to the appropriate light rays. Large matching ranges and red-green blindness will be produced by the tendency of both types of cone in the appropriate pair to respond to each kind of light ray instead of acting differentially.

The experiments reported in this book have given clear support to Houstoun's type of theory, with the modification mentioned above. It is not necessary to introduce separate kinds of receptor (such as " anomalous " cones), or the loss of certain forms of sensitivity, to account for the observed forms of colour-vision defect and variation. Within the four-colour scheme proposed by Houstoun there are sufficient modes of possible variability to account for all the kinds and degrees of difference and weakness of colour vision which have been reported. It is not necessary to have seven primaries, for example, when four will suffice, and, indeed, there is no evidence that orange, yellow-green, blue-green or violet are primary variables in any form of defective colour vision or colour weakness.

The question of brightness sensitivity must be considered separately. It is clear that brightness discrimination is not better among the colour blind, as sometimes suggested. They are more expert at utilising brightness differences as cues to what normal people call differences of hue and saturation, but they do not have smaller brightness thresholds than the normal. In the same way,

the blind are not, as often supposed, especially sensitive to hearing, but are simply more expert at using auditory cues as guides where those who are not blind would use vision. It is also clear with respect to the colour blind that the brightness levels of colours are not necessarily affected by losses of saturation and of hue discrimination, and the same applies to the colour weak and deviants in appropriate degree. It is true that red often tends to be darkened in the red-green blind, but the degree of its darkening is not correlated with loss of power to discriminate red from green (of equal brightness for them) even among protanopes. Among deuteranopes loss of saturation of red and green may be very great without any corresponding loss of brightness. Among red anomalous subjects about one half have red of normal brightness, but among green anomalous subjects the green is usually a little brighter than among the normal, and green anomalous subjects with darkened green have not been found.

Among minor defectives red and blue weaknesses may be associated with slight reductions of brightness in these hues, and a proportion of blue weak subjects have darkened violet, while yellow weakness tends to be associated with brightening of yellow.

In the factorial analysis of colour-vision variations it was likely that the general factor which corresponds to ability to do the tests, special colour-vision variations apart, depended largely on brightness discrimination. The first bipolar factor corresponded to red-green and the second to yellow-blue sensitivity. Brightness level was associated to some extent with hue sensitivity, but not always in a positive way, and to a very large extent it was independent. This strongly supports the hypothesis of a special brightness receptor. Evidence for darkness (or black) sensitivity is less convincing, and it is well known that the most intense experiences of black (as of white) can be explained by contrast effects. The most economical hypothesis consistent with the observed data would be that there is an independent brightness receptor, upon which the different wave lengths of light have effects variable among themselves and between individual subjects. Hue discrimination for red is not necessarily more impaired for protanopes than for deuteranopes, but brightness sensitivity for all red rays is greatly reduced. Among the yellow-weak brightness receptivity for yellow rays may be enhanced, while for blue rays it is often reduced among the blue-weak. Only by the hypothesis of an independent brightness receptor can it be understood that a red anomalous subject may have red of normal brightness. For those who wish to support a three-colour theory it will be necessary to show how brightness levels can vary independently of hue

sensitivities, and to show by what mechanism matching ranges may vary independently of deviations in two pairs of colour sensitivities at the same time but in such a way that yellow is variable separately from red and green. Piéron[5] has attempted to do this, but his explanation is probably more complex than the simple theory offered by Houstoun.

Granit's[6] experiments on electroretinography have led him to the discovery of " dominators " sensitive to the visible spectrum indiscriminately of colour (a) for scotopic and (b) for photopic vision, and of " modulators " sensitive to narrow spectral bands in photopic vision. The modulators varied somewhat among the different kinds of animals studied, but corresponded broadly to red, green and blue. Yellow is suggested as a sub-division of red sensitivity for the human eye. Many of the animals studied, such as the cat, guinea pig, rat and frog, are to the best of our knowledge totally colour blind, and Granit points out that the presence of modulators is not necessarily evidence of colour vision. Hence it is difficult to apply his results to human colour vision and its variations, though, as he points out, his scheme would provide a much more hopeful theory of colour vision in man than the three-colour theory.

From the point of view of the present experiments, Granit's dominator-modulator system might be used in the following way:[7] The scotopic dominator is not tested in these experiments, but the activity of the photopic dominator might be represented by the general factor found in the analysis of individual variations. The red-green and yellow-blue factors might represent the activities of two paired modulator mechanisms. The order of importance of these factors is represented (a) by their order in the analysis and (b) by the magnitude of their contributions to the total variance. The general factor is first in the analysis, but contributes relatively little to the total variance; the red-green factor is second in the analysis but makes a heavy contribution; the yellow-blue factor is third and its contribution is slight. The necessity that the modulator mechanisms should be bipolar is very clearly brought out in these experiments and in all studies of individual variations of colour vision which reveal these differences accurately. It is, however, not brought out by absolute threshold colour sensitivity tests, nor by differential threshold tests which depend on the comparison of one hue or saturation with another. It is brought out by tests of the Rayleigh equation type, and these are the ones which clearly differentiate the essential variations of colour-vision sensitivity. This bipolarity is not revealed by Granit's experiments, which are

essentially tests based on the absolute threshold principle, and this bipolarity is not taken into account adequately by any theory of colour vision but that of Hering with its modification by Houstoun which is supported by the results of the experiments reported in this monograph.

In his important researches upon the microstimulation of the human retina, Hartridge[8] has found evidence for the existence of colour modulators comparable with those suggested by Granit. Some evidence supported the theory that red, orange, yellow, yellow-green, green, blue-green, " indigo " (according to Hartridge a colour falling between blue-green and blue), blue and violet, are primary modulators. Hartridge has summarised the evidence from various sources in a table which shows that microstimulation of the human fovea supported red, orange, green and " indigo ", while fixation points in the human fovea were found for red, orange, yellow, yellow-green, green, blue-green, " indigo " and blue receptors. He gives a very interesting account of the nature of all the evidence supporting these possible primary modulators, nine in number altogether, and then puts forward a polychromatic theory of human colour vision, which he relates to that of Wundt and calls the Wundt-Granit polychromatic hypothesis. Such a theory would recall that of Edridge-Green in some ways, because there are seven primary modalities for colour on his theory.

In the present research the data are more likely to force us to employ at least four primaries than to compel us to utilise less than five in our theory. The facts of colour-vision variation discovered here would be almost impossible or perhaps quite impossible to explain on a three-colour theory. At the same time no evidence was found that they could not be explained with four primaries, provided white was accounted for, as in Granit's theory. It has seemed, however, absolutely necessary to think of these primaries as organised in two pairs of opposites, after the fashion of Hering and Houstoun.

In a more recent publication Hartridge[9] has advocated a theory of seven receptor functions for colour vision, which aims at combining the advantages of the Young-Helmholtz and Hering theories. This theory postulates that there are two systems of colour sensation, the first with three and the second with four primaries. The three-colour system is of orange-red, green and violet-blue. The second or four-colour system is of red-blue green, yellow and blue, the red receptor being also sensitive to the rays of the violet end of the spectrum. Hartridge shows that many of the problems of colour

vision could be solved on such a theory, especially that of the negative coefficients involved in three-colour matching experiments. His new scheme, however, would not meet the requirements that brightness should be regarded as due to an independent receptor system, which seems to be very important. As far as the present research can indicate, it has been pointed out already that all the problems of colour vision and of its variations met with in these experiments can be dealt with on a basis of four primaries for colour, acting in two pairs, and one for brightness. The research is more effective in stressing the need for at least four hue primaries than the need for less than five.

This need is also stressed by studies of change in electrical excitability of the eye following brief stimulation with coloured lights. In his experiments Motokawa[9a,9b] has given evidence that red, green and blue receptor processes are present in the fovea, and red, green, blue and yellow in the periphery at $15°$, $25°$ and $35°$ from the fovea. In a deuteranomalous subject the green process was weak, while the red process was missing in a protanope and the green process in a deuteranope.

Piéron[5] has put forward an important modification of the trichromatic theory, according to which there are three photo-sensitive substances, corresponding respectively to red, green and blue sensations and located in separate cones. To account for the independent variations of brightness levels he introduces the idea that there may be a fourth type of cone which contains all three substances in the proportions necessary to produce white, grey or a colourless sensation when stimulated by white light. Protanopia is accounted for by the lack of the red substance, while deuteranopia is explained by a lack of consistent relation between the red and green responding cones and their normal ganglion cells, so that the distinctions between red, green and yellow tend to break down. Red and green anomalous colour vision are explained by the presence in the red (or green) cones of some of the substance corresponding to the green (or red). The combination of the two anomalies tends on this theory towards deuteranopia. Partial lack of the blue substance gives rise to " tritanomalous " colour vision, often associated with darkening of violet.

The central difficulty in this theory is the lack of any way of accounting for the independent variations of yellow sensitivity found repeatedly in the present research. It seems impossible to avoid the view that there must be four primary cones and a mixed cone as well. When this is done, it may be that the differences between the form of the trichromatic theory advocated by Piéron

and the form of the four-colour theory adopted in this book will gradually be resolved. That both theories might be combined in a more comprehensive and adequate theory has been suggested by Burt.[10] Extreme yellow deviants might perhaps be called " tetranomalous ".

In private conversations about the present research both Dr. W. D. Wright and Dr. E. N. Willmer favour the view that yellow-blue defects might be due to pigmentation. They suggest that unusually small amounts of such a pigment might account for yellow weaknesses by admitting more blue light and therefore intensifying the blue responses, while excess of yellow pigment would admit less blue light than usual and therefore have the effect of producing blue rather than yellow weaknesses. It is difficult to see how such a theory could account for the differences between yellow-blue weaknesses (increased differential thresholds) and yellow and blue deviations (without increased threshold). Another difficulty is that yellow-blue weaknesses are not always associated with darkened violet, although the occasional tendency for blue to be confused with dark grey and yellow with light grey or white, in the defective, would accord with their theory. It might be a part explanation.

Both these workers also favour a theory of three variables, but Dr. Willmer would possibly suggest that only two of these need be differential receptors, because the third variable might be simply the effect of varying pigmentation. As explained before, it is extremely difficult or even impossible to think of all the variations of colour vision and brightness sensitivity as explained by three variables alone, and this matter need not be dealt with again. The writer is indebted to Dr. Alphonse Chapanis and Dr. Hl. de Vries for interesting correspondence on this subject, and, although the claims of the three-receptor theory are important, he feels that it is a duty to science to support the form of the four-receptor theory (with an additional receptor for brightness) advocated in this book, because it is far more adequate.

FREQUENCIES OF MAJOR RED-GREEN DEFECTIVES[11]

Up to the time of writing this chapter 178 major red-green defectives were tested, excluding 5 of the children tested by Mr. R. Brown, and one additional green anomalous man, one colour-blind Indian,* one man and one woman protanope, and one woman deuteranope, who could not be given the colorimeter tests. In

* Who explained his defects to me on a 'bus near Brighton.

populations of 989 males and 676 females tested in these experiments 7·6% of male and 0 59% of female defectives were found by chance. This accords with the results of other researches.[12,13,14,15] The expected frequency of female defectives on the single locus theory would be 0·61%, and the observed frequency does not differ significantly from this. The research therefore confirms the theory of sex-linkage and the reliability of the testing method is established. There are not in this group more defective women than would be expected. The " extra " ones claimed by some workers are almost certainly normal heterozygotes, some of whom are colour weak, or deviants, and who are doubtful passes on the Ishihara Test.

TABLE 117

NUMBERS OF MAJOR RED-GREEN DEFECTIVES : MEN AND WOMEN

| | PROT. | DEUTERANOPES | | GREEN ANOM. | RED ANOMALOUS | | TOTALS |
		Normal	Deviant		Red Dk.	Red N'l.	
MEN	43	36	25	39	6	6	155
WOMEN	5	1	5	10	1	1	23
TOTAL	48	37	30	49	7	7	178

If we split up the 7 8% of male red-green defectives in accordance with the frequencies for men shown in Table 117, percentages of the different types will be as shown in Table 118. The relative frequencies of the different types of women defectives are about the same as for men, though more women defectives were found

TABLE 118

PERCENTAGE FREQUENCIES OF MAJOR RED-GREEN DEFECTIVE MEN

| MEN | PROT. | DEUTERANOPES : | | GREEN ANOM. | RED ANOMALOUS | | TOTAL |
		Normal	Deviant		Red Nor.	Red Dk.	
155	2·16%	1·81%	1·26%	1·96%	0·305%	0·305%	7·80%

altogether than would be expected on the ratio of 0·61% of women to 7·8% of men. The reason for this is that most women in a family tend to be defective where one occurs, and the 23 women shown in Table 117 happened to include two sisters from each of three families and three sisters from each of two others. This is also the reason why the number of protanopes among them is almost as high

as the number of deuteranopes, although among men they are almost in the ratio of 4 to 6. If a sufficiently large sample of women could be obtained, no doubt the relative proportions of the different types would correspond exactly with the frequencies expected on the sex-linkage hypothesis. Any discrepancy, however, would have interest, since we do not know in detail what phenotypes correspond to the various heterozygous genotypes in women. The complexity of this problem will be apparent later.

Somewhat different proportions of major defective men have been reported by other workers. In 1927 Waaler[32] reported about 1% each of protanopes, deuteranopes and protanomalous subjects, but about 5% of deuteranomalous, making up 8% of defective men in all. In 1933, Wieland, according to Gates,[16] gave percentages as follows :—Protanopes : 1·4%; Extreme Protanomalous : 0·2%; Protanomalous : 0·6%; Deuteranopes : 1·3%; Extreme Deuteranomalous : 0·5%; Deuteranomalous : 4·0%—again making up 8.0% altogether. In 1935, Trendelenberg and Schmidt, again according to Gates,[16] found the following proportions of the four main types of defectives, this time calculated from the defective group itself : Protanopes : 26%; Deuteranopes : 13%; Protanomalous : 13·3% Deuteranomalous : 47·7%.

All these authorities indicate that there are more of the deuteranomalous class than of any other major defectives. The results of the present research would suggest that this might be due to the unintentional inclusion of a number of the moderate deuteranopes, who are more frequent than extreme deuteranopes, in the deuteranomalous group. Better methods of testing lead to the avoidance of this complication. The difficulty does not arise to the same extent in respect of the protanope groups, because moderate protanopes are much less frequent than extremes, but it might account for the rather large percentages of protanomalous subjects reported by the three authorities mentioned above. The same complication might account for Trendelenberg and Schmidt finding half as many deuteranopes as protanopes. It must not be forgotten, however, that considerable differences in relative frequencies of these types may occur in different areas, and the present research has sampled only the South West of Scotland.

Sex Differences

The experiments reported show no important sex differences in colour sensitivity except those connected with the forms of sex-

linked red-green defects. These will be dealt with in a later section. If the red-green blind and anomalous subjects are excluded from both sex groups, and if all women who are heterozygotes are also excluded, almost no sex differences remain. Apart from the colour blind and anomalous subjects, men are just as good judges of all colours as women; and apart from colour-blind and anomalous women and those who are heterozygotes for these major defects, women are just as good judges as men. Women may be more expert in the use of subtle colour names, and they may be more interested in colours than men, owing to tradition and social influences, but they are not fundamentally better at judging colour likenesses and differences than men. The popular theory that they are better judges of colour is probably due to the greater frequency of major defectives among men on the one hand, and to the fact that many colour names are more familiar and more commonly known to women than to men because social convention makes them more interested in colours on the other hand. In the four-colour test there seemed to be a possibility that men were more often yellow and women more often blue deviants, but failing more convincing evidence this remains merely a possibility. There is also the possibility that men are more scattered in mid-points, and this accords with their tendency to be more variable in other respects, such as intelligence.[29]

Colour Vision of Normal Heterozygotes[17]

Sex linked red-green colour-vision defects are incompletely recessive, since the heterozygotes for these defects and the normal condition usually have small red-green defects,[18,19] or may occasionally manifest the major defects themselves.[20] Details of the relationships between the different defective allelomorphs[21] and the small defects of these heterozygotes have not been fully revealed, but Table 119 shows the most marked characteristics of the red-green vision of seventy-seven women who have relatives with major defects, classified according to the defects of those relatives.

On the hypothesis of incomplete recessiveness, it would be expected that the heterozygotes for the normal condition together with a major red-green defect might show defects similar to those of their defective relatives, but on a very much smaller scale. This expectation is very largely fulfilled ($p < .01$) as Tables 12 and 60 suggested. Protanopes and deuteranopes tend to have red-green weak more often than deviant women relatives, while the green anomalous tend to have women relatives who are green deviants more often than

M

red-green weak. Furthermore, some protanopes have big red deviations and some deuteranopes big green deviations in addition to extreme loss of red-green discrimination, although their deviations are seldom as great as those of the truly anomalous, and it is interesting that the table shows that the women relatives of protanopes are

TABLE 119

WOMEN WITH MAJOR DEFECTIVE RELATIVES CLASSIFIED ACCORDING TO THE DEFECTS OF THOSE RELATIVES

GROUPING OF RELATIVES	GROUPING OF WOMEN				Totals
	Normal	Red-Green Weak	Green Deviant	Red Deviant	
Protanope	6	9	1	5	21
Deuteranope	7	20	4	0	31
Gr. Anomalous	6	1	12	1	20
Red Anomalous	2	1	0	2	5
TOTALS	21	31	17	8	77

more often red than green deviants, while those of deuteranopes are more often deviants in green than in red, when they are not red-green weak. The possible expectation was not fully confirmed that the red-green weak women relatives of protanopes might tend to have red of slightly diminished brightness.

If all the women who appear in the table were sisters of defective men, whose fathers were normal and whose mothers were ordinary heterozygotes, then the chance expectation of heterozygotes among them would be 1 in 2. The observed proportion of colour-weak and deviant subjects is 56/77 and this differs from the proportion of 1/2 by an amount which is more than can be attributed to chance. The discrepancy is due to the presence among these women of some who are daughters of defective men, mothers of defective men or women, or sisters of defective women, among whom the normal homozygous condition is not expected.

PIGMENTATION, RACE AND COLOUR VISION

No evidence was found that darkness of skin and hair pigmentation was associated with any tendency to colour-vision weaknesses among the normal, colour-weak or deviant subjects where there was

no evidence of racial difference. There was a tendency for yellow-blue defects to be more frequent among the group of subjects which included Jews, Indians, Turks and West Africans than among the others. When these were separated it was found that these weaknesses tended to be greater among Indians of Dravidian stock and greater still among West Africans than among the Jews, Turks or other Indians. This was specially interesting because of the theory that Dravidians are of a different racial stock from that of other Indians. The yellow-blue weaknesses, therefore, seemed to be associated with racial difference rather than with pigmentation except in so far as darkness of skin and hair pigmentation is itself a racial characteristic.

When all the subjects, concerning whom records of pigmentation were kept, are grouped in one four-fold table to compare frequencies of dark and fair colouring among the normal and the sex-linked defective groups, there is a small association between fairness and colour-vision defect. This is shown in Table 120, but is not a statistically significant difference.

TABLE 120

RELATIVE FREQUENCIES OF DARK AND FAIR AMONG NORMAL AND MAJOR
DEFECTIVE SUBJECTS

	Normal	Major Defective
Dark	248	67
Fair	323	105
Totals	571	172

It has been shown by Burt[10] that there is a small correlation between colour-vision defects and darkness of pigmentation. Vernon and Straker[12] showed that red-green defects were more common where the population of Britain might be supposed to be composed of the earlier settlers who were driven into the South and West by the Nordic invaders. Geddes[14] has shown that Fijians, who are possibly of Negro stock, are less often red-green blind than Caucasians, and Clements[22] that American Negroes and American Indians are less often red-green blind than American Whites. The present research shows that Dravidians and West Africans are more often yellow-blue weak than Whites, but in the population of the Glasgow district which was sampled in the experiments reported here, there is no connection between colour-vision defects and pigmentation. The best general conclusion would be that the differences of colour

sensitivity being observed in all these researches are probably racial characteristics, while pigmentation is also a racial characteristic and does not affect colour vision independently of their association in racial differences.

It has often been thought that the darkening of the red in protanopes might be due to pigmentation. Though it is a very unlikely theory indeed that a " minus red " filter of sufficient density to produce the observed degree of darkening of the red in protanopes could exist in the eye without being seen by direct inspection, there is some interest in comparing the frequencies of dark and fair with the frequencies of protanopes and deuteranopes. These frequencies are shown in Table 121. Green anomalous subjects are included, though they do not have darkened red, and all red

TABLE 121

PROPORTIONS OF DARK AND FAIR

	Prot.	Deut.	G. Anom.	R. Anom.	Totals
Dark	21	24	15	7	67
Fair	27	41	30	7	105
Totals	48	65	45	14	172

anomalous subjects are put together, although the red is darkened in only seven of them. Green anomalous subjects tend to be fair, in so far as the numbers represent a good sample of the population. There is a small difference suggesting that protanopes tend to be dark, but if the anomalous subjects are excluded the excess of protanopes who are dark is not statistically significant.

The possible connection between race and colour-vision variations was brought out clearly by the work of Rivers,[23,24] who used Holmgren's wools, Lovibond's tintometer and Nagel's cards, in testing natives of Murray Island, of Upper Egypt, and in two Indian groups: the Todas, and the Uralis and Sholagas. The scientific value of results gained with the wools and the tintometer are seriously open to question, but red-green blindness was found to be exceptionally common among the Todas, though never found among Papuans. Sensitivity to yellow and particularly to blue were found to be decidedly lower than in white races, and Rivers regards this as confirming the view that the inadequate nomenclature for blues found often among primitive races is connected with a weakness in that colour. This would be confirmed by the findings of the present research, weaknesses in yellow and blue being the most frequent

colour-vision defects in white peoples, but decidedly more frequent among the members of dark-skinned races.

Colour Vision of Children

In a research on 525 boys and 252 girls, between 5 and 15 years of age, Mr. Robert Brown found that the Ishihara Test showed no differences in the frequencies of major red-green defectives in comparison with adults. Of these children 81 boys and 36 girls also did the Four-Colour Colorimeter Test, and, after excluding 6 boys and 1 girl who were major defectives, there were no significant differences from normal adults in the distributions of red-green and yellow-blue matching ranges or deviations.

Personality, Temperament and Colour Blindness

In at least three ways the relationships of temperament and personality to colour-vision defects are interesting. The first may be illustrated by a short experiment which was carried out with seven major red-green defectives and a group of many normal men taken at random. All the subjects were well known to the writer, and he entered notes of any temperamental peculiarities they showed during the Rotating Disks Test in a suitable table. It became clear from an application of the Chi-squared technique that the colour-blind group showed significantly more peculiarities of temperament and personality than the group with normal colour vision.

An attempt was made to have this experiment continued by a student, but it was abandoned owing to adverse circumstances beyond control. However, there is no doubt that a carefully planned research on this matter would be of great interest. It would be likely to support a form of Adler's theory that abnormalities of personality are traceable to the influence of " organ inferiority ". Such a research would require the application of a variety of tests of personality to a random group including normal and colour-blind subjects by a tester who did not know which were colour blind. A number of special points would have to be taken into account. The question of the subject's consciousness or otherwise of his defect would be important, and it would be necessary to show how far the abnormalties of personality were due to other and more fundamental causes. Personality tests alone would not be sufficient, and careful case histories would have to be taken as well, to show how the " organ

inferiority " of colour blindness had affected the subject at different ages and in different situations.

The second way in which the subject's temperament is related to colour blindness may be illustrated from certain deuteranopes. The first was an extreme defective in red and green with a large yellow weakness as well. He was a University lecturer in Logic, and did not admit his defect, though all his friends knew that he was colour blind. He regarded himself as having an exceptional ability to see certain colours which ordinary people could not see. This was supported by his frequent use of colour names in ways to which other people objected—sometimes he used several names, such as " red ", " green " and " a dirty colour ", where they saw no differences, and at other times he used one name where they saw several distinct hues. From what has been said in other chapters it will be clear to the reader how this can happen, and how a major defective can even gain the reputation of being exceptionally sensitive by continually doubting colour matches made by other people. The present subject's theory that he could see special colours was also supported in his judgment, though quite erroneously, of course, by his ability to read those plates in the Ishihara Test which normal people find almost illegible. Not understanding the principle on which these plates are made, he drew the inference that he could see colours invisible to them.

Like many other colour-blind people of a thoughtful and analytic temperament, who have an inquiring and sceptical turn of mind, he was extremely clever at exploiting all manner of indirect clues which indicated colour differences which he could not see, and after much practice did this almost unconsciously. The result was that he never made hasty or ill-considered judgments about colours, and was very seldom wrong in daily life, which confirmed his false impression that his colour vision was very good. He was like another extreme deuteranope who also refused to admit his own defects, and who carried out a piece of serious " scientific " work on the influence of colour filters on the accuracy of readings with range-finders in the 1914-1918 war. It is not surprising that the results were negative.

The third was a moderate deuteranope and he illustrates the effect of the opposite attitude. He was also a very intelligent man, a lecturer in engineering, objective in outlook, and preferred to make gross errors in colour naming than to spend any time or effort over making careful analyses or learning to take advantage of second-ary clues. Hence, though he was often right by accident in colour

naming, and then felt triumphant, he was equally often wrong, and then laughed heartily and corrected himself if possible. Instead of hiding his defect, he displayed it, like a woman deuteranope who used her disability to amuse and astonish her friends. On the whole the engineer subject made far more errors than the logician, though the latter was at least twice as defective.

These kinds of temperamental influences, in various forms and degrees, affect all colour-blind people, and often make the practical consequences of their defects in daily life difficult to correlate closely with the measurements of those defects made in the laboratory.

The third form of personality influence on colour vision is generally due to fear of colours traceable to infantile experiences. The writer has reported elsewhere,[25] a case of total colour blindness of hysterical origin. The subject was an extreme deuteranope at best, but he lost his colour vision entirely at an early age, owing to fear of being strangled by his mother with a brightly coloured scarf which she twisted round the child's throat one day to protect him when he had a cold. As an adult he had an hysterical breakdown with a personality change which involved a regression to the phase of childhood before the event with the scarf. This change brought back his colour vision (as a deuteranope) but at the same time he lost his memory for current events. The change gradually reversed itself as he recovered, and he became totally colour blind again but regained his normal adult memories. By hypnosis he was enabled to recall the terrifying incident of the scarf in childhood, and recovered the colour vision of a deuteranope permanently.

This case is concerned with too many psychiatric problems to be dealt with fully here, but there is no doubt that occasional forms of colour defect might be due to the process of dissociation resulting from fear, and that their detailed study would be extremely interesting if they could be found and satisfactorily analysed. The writer has met with two other cases in which there was a suggestion of hysterical origin : one a woman protanope with darkened violet and darkened green, and the other a woman red anomalous subject, but it was not possible to investigate these cases adequately from the psycho-analytic point of view.

ITEM-ANALYSIS OF THE ISHIHARA TEST

In order to answer two further questions about the Ishihara Test, a complete item-analysis was made of Plates 2 to 25 of the 8th Edition of the Test (Kanehara, Tokyo, 1939). The two questions

were : (1) Whether any plates can be found which are specially good for distinguishing particular types of defectives; and (2) Whether a shortened and more reliable form of the test can be made by selecting certain plates and excluding others.

The item-analysis was carried out on the results of testing 239 normal and 145 major defective subjects, all of whom also did the rotating disks or colorimeter tests. They were classified into fifteen groups, as shown in Table 122. Some subjects had to be transferred to yellow and blue minor defective groups from other groups (as shown in sections on the Ishihara Test in earlier chapters) for the purpose of this section, because yellow and blue were not considered before. Also some new subjects have been added here.

This version of the Ishihara Test consists of six sets of four plates, excluding the first plate, which is a " joker " and is used for showing subjects what to do and for excluding malingerers who wish to be thought colour blind. This plate and the remaining seven " wavy-line " plates, which are for testing non-readers, will not be considered here. Each set of plates was dealt with separately by estimating the order of reliability of its four plates for each type of subject. This was done by working out a " negative score " for each plate for each of the fifteen groups of subjects tested. The negative score was the sum of errors and abnormal readings given, in the case of normal and minor defective subjects, and the sum of errors (from their point of view) added to half the sum of the false alternative readings given by major defectives. The difference in the method of scoring was due to the fact that no alternative reading can be regarded as in any way right for the normal, but may be regarded as partly right for the major defectives.

Plates 2—5 show pink figures on green backgrounds, each with an alternative which is correct for major defectives. Plates 6—9 show green figures on pink backgrounds, also with an alternative reading for major defectives. The item-analysis showed in general that Plates 2, 3, 6 and 7, in which there is a single figure, were reliable for normal subjects but not for major defectives, while Plates 4, 5, 8 and 9, in which there is a double figure, were reliable for major defectives but not for normal subjects. None of these plates had any capacity to distinguish any type of major or minor defective better than any other.

Plates 10—13 show a pink figure on a green background, and 14—17 a green figure on a pink background, without any reading for major defectives. Among these plates 10, 11, 14 and 15, in which there is a single figure, were reliable and did justice to all types of

subjects, while those in which there is a double figure, namely 12, 13, 16 and 17, were unreliable because they suggested too many alternative interpretations. None of these plates was better for any type of subject than for any other type.

In Plates 19—22 the major defectives should read a greyish figure on what is for them a fawn or greenish background, while normal subjects should see a multi-coloured background without any figure. None of these was very reliable for any type of subject, normal or abnormal.

In Plates 23—25 the normal subjects read a double figure, one digit being red and the other magenta, on a dark grey background. Major defectives with darkened red are supposed to see the magenta figure and others the red figure, as explained elsewhere. These plates are very reliable for normal subjects, who seldom make errors or give alternative readings for them, but they are very unreliable for all types of major defectives.

In making a shortened form of the test, Plates 10, 11, 14, 15, 18 and 23 were chosen. Plates 10, 11, 14 and 15 were the most reliable for all types of subjects, normal and abnormal, while it was considered an advantage to have at least one plate which the defectives could be expected to read, and one plate which might give some indication of the difference between those with and those without darkened red, and Plates 18 and 23 seemed best for these purposes respectively.

Table 122 was then drawn up to show the numbers of errors made by different types of subjects on this set of six plates. The average major defective made about 5 errors, and the exclusion of Plate 23 would make the short test more reliable for them. The normal subjects and minor defectives made about 0·4 errors (on all six plates together), while the exclusion of Plate 18 would make the shortened test more reliable for them. No type of minor defective could be effectively distinguished, though the numbers of errors ranged from none for blue deviants to 0·67 for green deviants. The extreme deuteranopes, red anomalous and protanopes were the most consistent failures among the major defectives, while the green anomalous tended to give the largest variety of alternative readings and often to be able to see the normal as well as the " defective " reading for many plates. Deviant and moderate deuteranopes fall between these extremes. It would not be possible, however, to distinguish the type of any major defective as an individual. In this, as explained before, the Ishihara Test must be ranked as a complete failure, and on its basis we should have no clear idea of types of major defectives at all.

M*

This shortened form of the test would have the advantages of quickness, and of unequivocally separating major defective subjects from the normal and minor defective types, but it would have the

TABLE 122

FREQUENCIES OF "COLOUR-BLIND" READINGS ON SIX PLATES OF THE ISHIHARA TEST: 239 NORMAL AND 145 MAJOR DEFECTIVE SUBJECTS

Subjects:		Plate Number and Errors:						
No.	Type	10	11	14	15	18	23	Average of Errors
65	Normal	0	1	0	0	18	0	0·29
29	R. Dev.	1	2	1	1	13	0	0·62
21	G. Dev.	2	2	2	2	5	1	0·67
51	R-G. Weak	1	7	0	1	15	0	0·47
9	Y. Dev.	0	0	0	0	4	0	0·44
9	B. Dev.	0	0	0	0	0	0	0·00
55	Y-B. Weak	1	0	1	1	14	0	0·31
42	G. Anom.	25	31	29	30	30	9	3·67
20	Dev. Deut.	17	18	19	18	18	15	5·25
21	Mod. Deut.	16	16	16	16	16	10	4·29
14	Ext. Deut.	14	14	14	14	13	14	5·92
7	R. Anom.(N.R.)	5	6	6	6	6	6	5·00
7	R. Anom.(D.R.)	7	7	6	7	5	4	5·24
10	Mod. Prot.	9	10	9	9	10	4	5·10
24	Ext. Prot.	24	24	24	24	24	5	5·21

serious disadvantage of being very short and would offer the tester a very small number of sub-tests although he might keep the other eighteen for use if any difficulty arose.

THE YELLOW-BLUE AND BLUE-GREEN PLATES IN STILLING'S TABLES

A number of subjects in the rotating disks and colorimeter tests were asked to read the yellow-blue and blue-green plates in Stilling's Tables (17th edition, Leipzig, 1926), in order to study the validity and reliability of these plates as tests of yellow-blue weaknesses, for which they are intended.

The subjects were classified as follows:—

Absolutely Normal:	13 men;	26 women
Red-Green Weak:	4 men;	16 women
Yellow and Blue Deviants:	11 men;	10 women
Yellow-Blue Weak:	35 men;	23 women
Total of Normal and Minor Defectives:	63 men;	75 women

Green Anomalous	3 men;	1 woman
Red Anomalous:	1 man;	0 women
Deuteranopes:	13 men;	0 women
Protanopes:	10 men;	4 women
Total of Major Defectives:	27 men;	5 women

The plates used in Stilling's Tables were as follows :—

X_1 $(^{92}_{54})$; X_2 $(^{76}_{83})$ — yellow on blue.
XI_1 $(^{42}_{63})$; XI_2 $(^{49}_{46})$ — green on blue

They were read at a distance of one metre and were illuminated by a 60-watt daylight lamp.

Comparisons were made between the frequencies of normal readings and of errors ("other" and " no " readings) for absolutely normal subjects and five groups of defectives : red-green weak; yellow and blue deviants; yellow-blue weak; major defectives together; protanopes alone. The Chi-squared technique was used.

It was found that Plates X_1 $(^{92}_{54})$ and X_2 (76) were correctly read by all subjects except protanopes, who made a significantly larger proportion of errors than those who were absolutely normal, though not enough to be detected by these plates consistently. Plate X_2 (83) was quite unreliable and gave numerous errors with all types of subjects.

Plate XI_1 (42) was significantly more difficult (on the 0.02—0.05 level) for major red-green defectives, and for the yellow-blue weak (on the 0.01 level) than for normal subjects, but could not be used to detect them consistently enough to be of practical value. Plates XI_1 (63) and XI_2 $(^{49}_{46})$ were quite unreliable for any types of subjects, normal or defective.

It is suggested that the difficulty of making a pseudo-isochromatic test for minor yellow and blue defectives is likely to be even greater than for minor red and green defectives, because they are more widely scattered. No sharp dividing line has been found between " normal " and major defectives in the study of yellow-blue vision, comparable with the divisions between " normal " and major red-green defectives, and which makes the use of pseudo-isochromatic tests of red-green " blindness " practicable. The most extreme yellow-blue defective, who might reasonably have been called yellow-blue " blind " was able to read the yellow-blue plates (X_1 and X_2) with a little difficulty. Nevertheless, the blue-green plates (XI_1 and XI_2) correspond to the commonest confusion made by those with a blue defect, namely the confusion of blue with green,

while Plates VII, VIII and IX, correspond to the commonest confusion made by those with a yellow defect, namely that between yellow and orange (though lack of time prevented their study in this research).

INHERITANCE OF MINOR WEAKNESSES

No consistent tendency can be found for the minor individual differences of matching range or deviation among the normal group of the population to be associated with sex. On the other hand it is quite clear that the major individual differences, including anomalous colour vision, protanopia and deuteranopia, are commoner among men than among women, in a proportion corresponding to expectation based on the theory of sex-linked inheritance. This corresponds with the evidence, which is very strong, that the types of major red-green defective are discontinuous variations.

Since the red-green and yellow-blue minor defects of the " colour weak " and the red, green, yellow and blue minor defects of the " deviants " are shown to be equally common in men and women, they are not totally sex-linked. Similarly, darkened violet cannotbe sex-linked. Numerous studies of families whose members show minor defects, however, indicate that they are inherited, though they are continuously variable in the statistical sense. From all such studies women with colour-blind or anomalous relatives must be excluded, because it is evident that any special defects they show are due to their having among them a high proportion of normal heterozygotes for major red-green defects.

Several possibilities must be considered in connection with the inheritance of minor defects. In the first place, one experiment, the four-colour test, suggested that blue deviations were slightly more common among women and yellow deviations among men. This difference, if upheld by further research, might be due to differences in the habits of the two sexes, as, for instance, to smoking pipes and cigars, which is commoner among men than among women. Also, it might be due to sex-controlled inheritance, in which there is no genetic sex-linkage, but the character in question tends to appear more freely, or even exclusively, in the physiological environment for the genes provided by one sex rather than in that of the other. Dominant white forelock, found exclusively among men, but not sex-linked, is the best known example of a sex-controlled character in human heredity.[26] The appearance of a character, in this case a minor colour-vision defect in yellow, more freely in men than in women, might be due to the gene being located on the non-pairing portion of

the Y chromosome (holandric inheritance), when the character is passed on directly from father to son.[27]

Although minor colour-vision defects are not associated with sex, except for the possible exception just mentioned, it is still possible that some of these defects may be due to partial sex-linkage. This is a form of sex-linkage in which the gene has its locus upon the small part of the sex chromosomes which are common to both sexes.[28] In the population at large a character so inherited will be found equally frequently in both sexes, but if its inheritance in particular families is studied, it will be found to be more common among the men in some families and among the women in others. Some evidence suggested this possibility during the course of the researches here reported. For example, in one family yellow-blue weaknesses appeared in father and son, but not in either daughter, while in another family this weakness appeared in the mother and two daughters, but not in the son. Careful notes were therefore kept of a large number of family groups, and all possible combinations were found equally freely. Some families showed yellow-blue weaknesses in all members irrespective of sex, some in father and daughter, others in mother and son, or in one son or daughter and not in the other. In two families in which red-green major defects were inherited by the sex-linked mechanism, yellow-blue weaknesses were also inherited irrespective of sex, though most of the families which showed sex-linked red-green defects did not show any yellow-blue weaknesses at all. Nevertheless, the evidence that there might be a sex difference in minor yellow-blue defects concerned deviations, while it is likely that most of the evidence which indicates no connection with sex concerns colour weaknesses in yellow and blue. It is possible that there is more than one type of yellow-blue defect, each possibly sub-divided, and that one form of yellow deviation is totally sex-linked in the holandric manner, while one or more of the other forms are partially sex-linked, and the possibility of sex-control for some forms of minor yellow-blue defect cannot be excluded with certainty. The same applies in a parallel way to minor red-green weaknesses (excluding the weaknesses of normal heterozygotes), except that there has been no suspicion of sex-control or holandric sex-linkage here.

In general, however, minor colour-vision defects are definitely inherited, being more frequent among relatives than among those unrelated, and appearing among relatives in characteristic form. What is inherited is not a general tendency to colour-vision weaknesses of a minor kind, which may take any form. In addition there is a

tendency for these weaknesses to be less marked in offspring than in parents, in accordance with Galton's well-known principle, illustrated by the fact that children of tall parents are generally less tall than their parents but taller than the mean for the population at large. Such results might be explained most easily on the assumption of several pairs of genes, producing identical or slightly different effects, but interacting or combining instead of being mutually exclusive like dominant and recessive allelomorphs.[36] In the operation of additive genetic effects, the more extreme a subject in the character in question, the more is he homozygous for all or any of the pairs of genes concerned, while the intermediate subjects tend to be predominantly heterozygous for all the pairs of genes, or homozygous for equal numbers of opposed pairs. This is probably the way in which most normally or continuously distributed characters such as height and intelligence are inherited.[29] For example, if there were three pairs of genes controlling blue deviation, three controlling yellow deviation, and four pairs of genes controlling the magnitude of the yellow-blue matching range, all inherited independently and acting in an additive way, not sex-linked, then an effect such as that actually observed might result. A similar but independent system of pairs of genes producing red and green deviations and red-green matching ranges would have to be assumed, but they would operate independently from the well-known sex-linked allelomorphs of red-green major defects. From the normal distribution of red, green, yellow and blue deviations (apart from sex-linked anomalies), it would be inferred that genes producing red are as common and as effective as those producing green deviations, and the same for yellow and blue. Since the spread of variations in yellow-blue deviation is greater, however, it might be inferred that the number of pairs of genes at work in the yellow-blue system would be considerably larger or their effects greater. From the fact that the matching ranges are strongly skewed, it might be inferred that the genes producing large matching ranges (apart from sex-linked colour blindness) in red-green, or in yellow-blue vision, are much less effective than those producing small ranges. Since yellow-blue ranges are larger than those in red and green the number of pairs of genes operating in yellow-blue vision, or their effects, might be larger, just as it would seem to be in the control of mid-points. In addition, it must be emphasised that the genetic constitution, or genotype, is but one system of factors influencing the development of the living individual, or phenotype, and this applies in all studies of heredity. Varying environment and varying expressivity of the genes will

account for some observed differences, and will smooth out the step-wise distributions produced theoretically by the hypothetical pairs of genes mentioned above. The apparently greater scatter of mid-points in men might be due to holandric inheritance of additive genes.

INHERITANCE OF MAJOR DEFECTS[21]

The evidence is very strong that the defects of red-green vision found in protanopes, deuteranopes, and in red and green anomalous subjects are totally sex-linked. That is to say, these conditions are discontinuous variations from those of normal red-green vision, and are alternatives to them, determined by the appropriate genes carried on the non-pairing part of the X chromosome. Their discontinuous nature, however, has never before been fully established, and the different forms of red-green major defect mentioned above have often been assumed to be variable effects of the operation of one allelomorphic gene contrasting with the normal condition. There are, in consequence, several points of interest which deserve attention, and these may be mentioned now.

Firstly, it is easy to distinguish anomalous subjects from the most extreme or the ordinary deviants. The deviants rarely have a mid-matching point outside the limits of $\pm 3 \times$ sigma, which puts them as a class within the limits of normal variation, while the deviations of anomalous subjects are seldom less than $\pm 6 \times$ the sigma for the normal group, which puts them a long way outside these limits. One or two of the most extreme red and green deviants, however, were able to produce some evidence arousing suspicions of sex-linkage, though very slender. For instance, one extreme green deviant reported that his maternal uncle had been failed in a colour test for the Mercantile Marine, while an extreme red deviant reported the same of his maternal grandfather. Now it is possible that the uncle of the one was green and the grandfather of the other was red anomalous, or that they had other forms of major red-green defect, and that the deviations of the subjects tested, though not sufficient to class them as anomalous themselves, were two cases in which the physiological environment of the sex-linked genes was not suitable for a full development of the appropriate characters in the phenotypes. There are other possibilities, but it is most likely that the genes for the defects of the deviants were segregating in a way not sex-linked and quite independent of those for the defects of their major defective relatives. Nevertheless, such cases are rare, and in general there is no difficulty in establishing the independence

of red and green normal deviations and red and green anomalous conditions. In just the same sort of way, and again with a small number of interesting exceptions, it can be shown that protanopes and deuteranopes are discontinuous with ordinary small variations of matching range which are not sex-linked like the major defects.

Secondly, there is some evidence that, if exceptional fatiguability is a distinct form of colour-vision defect, it is also sex-linked, because, so far as it was observed in this research, it occurred only in men. Again, it might be totally sex-linked, or follow the exclusively male sex-linked pattern, being passed on from father to son without ever occurring even as a recessive in women. It is very unlikely to be partially sex-linked, because then, on the average, it would be found as frequently in either sex.

Thirdly, it is clear that in heterozygous women who inherit one gene for a major red-green defect and one for normal colour vision some degree of defect may be observed and measured much more frequently than in normal women. This small defect is usually an exceptional red-green matching range, and it seems very likely but has not been proved that the heterozygote for the red anomalous condition is always a red deviant, though that for the green anomalous condition is most often a green deviant; that for deuteranopia red-green weak, and that for protanopia red-green weak without slight darkening of the red. We have little information about the heterozygous phenotypes for the major red-green defects in con-bination. Further difficulties arise because it is not often possible to be certain to what genotype in a woman a given phenotype corresponds.

In an attempt to clarify the problems of the inheritance of major red-green defects, certain pedigrees have been compiled from the data of the present research. They have been classified in the following way : (a) Father and son; (b) Father and daughter; (c) Mother and son. No family in which there was a colour-blind or anomalous woman has included a colour-blind or anomalous mother and daughter together. It has also been most unfortunate that the fathers of several green anomalous and colour-blind women were dead or inaccessible, and that where a daughter or son and father could be tested there was often no sibling of the other sex. Although many relatives have been most generous in giving their time for the laboratory tests, others have been adamant in their refusal, and the writer has been forced to accept defeat with a good grace. Material of this kind can be accumulated but slowly, and it is to be hoped that persistent research will gradually fill the gaps, in the

course of time. Nevertheless, the following pedigrees show several important points.

(a) *Father and Son**

Pedigree I.

$$\male \text{ d} \times \female \text{ H?}$$
$$|$$
$$\male \text{ d}'$$

Pedigree II.

$$\male \text{ d} \times \female \text{ H}$$
$$|$$
$$\male \text{ d}$$

Pedigree III.

First
$$\male \text{ N?} \times \female \text{ H?} \times \male \text{ N?}$$
$$|\quad\quad\quad| \text{ Second}$$
$$\male \text{ p?}\quad \male \text{ p} \times \female \text{ H?}$$
$$|$$
$$\male \text{ d}\quad \male \text{ N?}\quad \male \text{ N?}$$

Pedigree IV.

First
$$\female \text{ H?} \times \male \text{ N} \times \female \text{ H?}$$
$$|\quad\quad| \text{ Second}$$
$$\male \text{ d}\quad \male \text{ p}$$
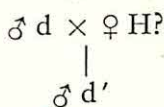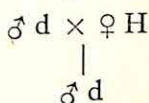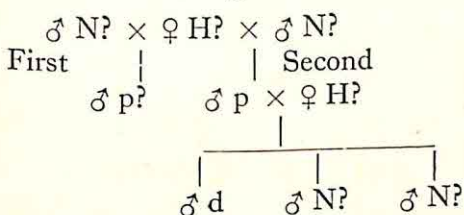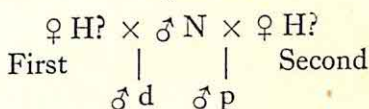
In these pedigrees, in which father and son were major defectives, both were efficiently tested. In Pedigree I father and son had different defects, and in II the same. In III the father was a protanope and the son a deuteranope. In IV there were two sons with different defects, one by each wife, but in III two sons with the same defects by different husbands. In II the mother was a heterozygote according to the tests, but in the other pedigrees there was no direct evidence. The easiest explanation in all these patterns is to suppose that the mother was in each case a heterozygote for the defect shown by her son. This was the same as that of the father in II, but not in I or III.

Nevertheless, it must be said that we cannot absolutely exclude the possibility of (xx) and y chromosomes in the mother in II, in which case the son might gain the father's defect in his X chromosome[16,30]. We have good evidence of independent segregation of protanope and deuteranope genes, and in III sons of the same mother had the same defect but her grandson was different. This, however, depends on accepting hearsay evidence of good quality that the untested son by the first husband was a protanope. In IV the two mothers of the half-brothers by the same father must have been heterozygotes for different defects.

*In these pedigrees the following notation will be used:— $\male$ = male, $\female$ = female, N = normal, H = heterozygote, p = protanope, d = deuteranope, d' = deviant deuteranope, g = green anomalous, r = red anomalous without and r' = red anomalous with darkened red, ? = not tested by the writer.

(b) *Father and Daughter*
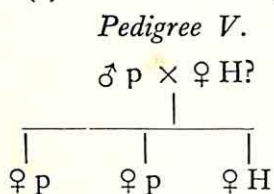
Pedigree V.
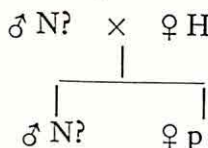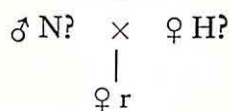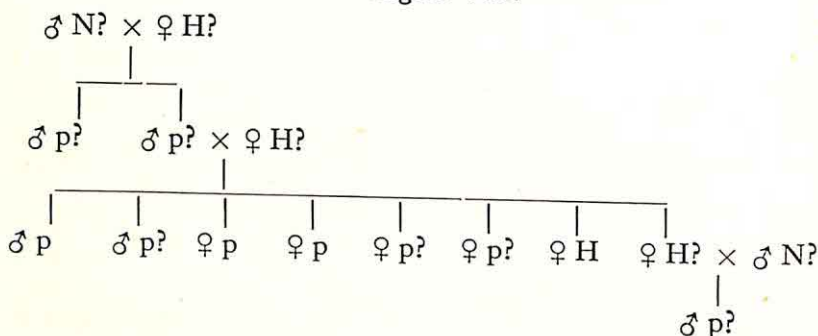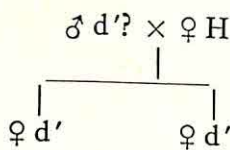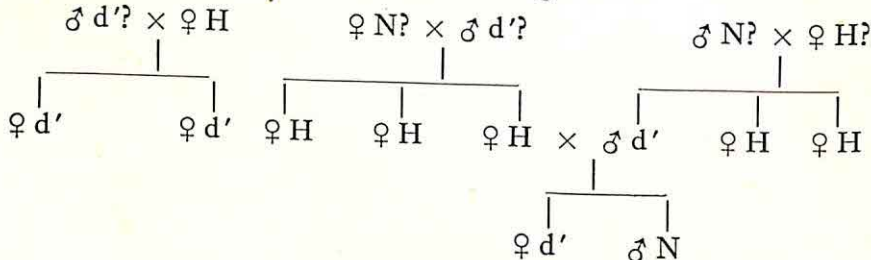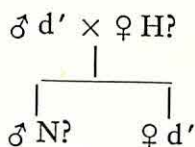
♂ p × ♀ H?

♀ p   ♀ p   ♀ H

Pedigree VI.

♂ N? × ♀ H?

♂ N?   ♀ p

Pedigree VIa.

♂ N? × ♀ H?

♀ r

Pedigree VII.

♂ N? × ♀ H?

♂ p?   ♂ p? × ♀ H?

♂ p   ♂ p?   ♀ p   ♀ p   ♀ p?   ♀ p?   ♀ H   ♀ H? × ♂ N?

♂ p?

Pedigree VIII.

♂ d'? × ♀ H

♀ d'   ♀ d'

Pedigree IX

♀ N? × ♂ d'?

♀ H   ♀ H   ♀ H × ♂ d'

♀ d'   ♂ N

♂ N? × ♀ H?

♀ H   ♀ H

Pedigree X.

♂ d' × ♀ H?

♂ N?   ♀ d'

Pedigree XI.

♂ d? × ♀ H

♀ g

Pedigree XII.

♂ d? × ♀ H

♀ g

Pedigree XIII.

♂ d × ♀ H

♀ g   ♂ N

Pedigree XIV.

♂ d' × ♀ H

♀ g

Pedigree XV.

♂ d? × ♀ H?

♀ d × ♂ N?

♀ H

Pedigree XVI.

♂ d × ♀ H   ♂ N   ♂ N?   ♂ N?

♀ g   ♀ g   ♀ g

Pedigree XVII.

♂ g? × ♀ H? (for d)

♂ N?   ♂ d′ × ♀ H (for g)   ♂ d   ♂ d?   ♂ N

♀ g

Pedigree XVIIa

♀?× ♂ r′   ♂ r′?

♀ H (for r′)× ♂ p

♀ r′   ♀?   ♂ N

Pedigree XVIIb

♀ H (for d′) × ♂ d′

♀ d′   ♂ d′   ♂ d′   ♂ N
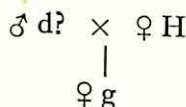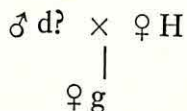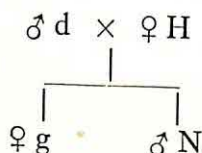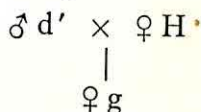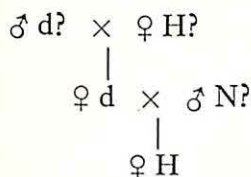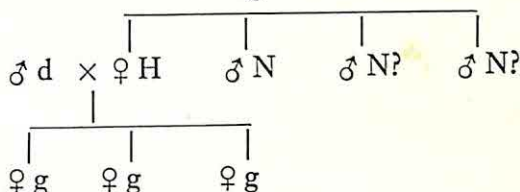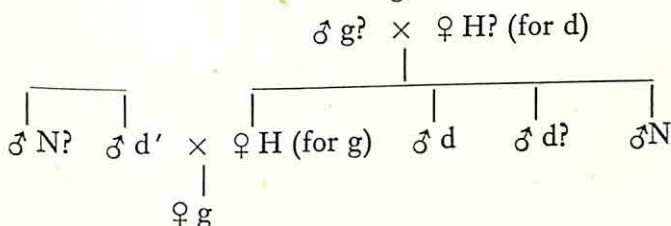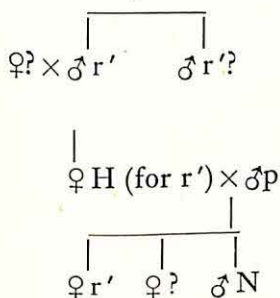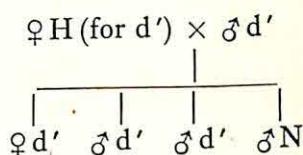
Among these cases it is apparent that the same degree and kind of defect appears in father and daughter in Pedigrees V, IX, X, and probably in VIII, in which the father was tested at home with the Ishihara Test by one of the daughters who was a very reliable tester. In VI and VIa the daughter would appear to be the only defective member of the family; in VI father, mother and brother were all tested at home with the Ishihara Test, but in VIa this was impossible. In VII there was hearsay evidence that father, untested sibs and the son of one of them, were all extreme protanopes. It is my experience that this sort of evidence may be granted some credence, especially when given by several people who know their own defects very well and do not seek to hide them, as in this family. A person does not often become notorious in a family circle for certain kinds of errors in colour naming and matching unless he is a major defective.

In XI and XII there was good hearsay evidence that the fathers, now dead, had defects more obvious than those of the green anoma-

lous daughters, because their defects were not known until the tests were done, whereas their fathers were reputed to be colour blind. The evidence did not suggest darkening of the red end of the spectrum. In XIII, XIV and XVI and XVII adequate tests proved that the father was a deuteranope and that the daughter was green anomalous.

Thus we have evidence that daughters can follow their father in being either protanopes or deuteranopes, and the degree of the father's defect was reproduced in the daughter in at least three cases. There is also evidence that the daughter can be green anomalous while the father is a deuteranope, or red anomalous while he is a protanope and the maternal grandfather is red anomalous. The exceptional Pedigrees VI and VIa will be found to support the two-locus theory of Waaler. Where the daughter follows the father it is not by any means certain that the mother was heterozygous for the same defect. The father's defect may have been dominant to any other type of defect recessive to the normal condition in the mother. Where the daughter does not follow the father it is clear that her condition must be dominant to his and must be the same as that for which the mother is a heterozygote. The latter state of affairs occurred in XIII, XIV, XVI and XVII, and probably in XI and XII. The green anomalous condition would therefore appear to be dominant to that of the ordinary and the deviant deuteranope. In XVIIa red anomaly is dominant to protanopia.

Where all the sibs are alike it is reasonable to suppose that we are dealing with a family in which both parents had the same defective gene, and the daughters are then true homozygotes for that condition. This occurred in family VII. Where the family is small it is not so clear. In VIII and IX it is clear that the mother must have been heterozygous for deuteranopia or a condition recessive to it, and in V for protanopia or a condition recessive to it. Thus in VIII and IX the defective girl's mother was not a heterozygote for the green anomalous condition. Beyond that the reader may draw his own inferences. We are in a position to draw the conclusion that the six types of major defective genes look very much like multiple allelomorphs, and we have evidence of their probable order of dominance. Further observations will be made about this problem.

If we turn for help to a consideration of the kind of defect, if any, shown by the women relatives of women who are major redgreen defectives, a certain amount of interesting evidence is found. In pedigrees V and VII, in which there were women protanopes and in which there was nothing to lead us to suspect that any of these women were heterozygous defectives, there was in each pedigree a normal heterozygous sister who was red-green weak without any

deviation. Similarly, in pedigrees VIII and IX, in which there were women deuteranopes, of the deviant type, not suspected of being heterozygous defectives, their women relatives were again red-green weak but with a green deviation; in VIII the mother was thus affected and in IX the mother and her two sisters, and also the two sisters of the father (who was a deuteranope like his daughter). On the other hand in pedigrees XI and XII, in which daughters were green anomalous and suspected of being heterozygotes with deuteranopia recessive, the mothers were green deviants. In XIII, XIV, XVI and XVII, which differed from XI and XII only in the respect that the father was tested and proved to be a deuteranope, the mother was again in all cases a green deviant. In XVIIa the mother was a red deviant with darkened red. Hence, in so far as it is true that the normal heterozygotes for protanopia or deuteranopia tend to be red-green weak, appropriately with or without deviation, while those who are normal heterozygotes for either of the anomalous conditions tend to be deviants and not red-green weak, these additional data give decided support to the view that the green anomalous daughters were heterozygotes with deuteranopia recessive, while the red anomalous daughter was a heterozygote with protanopia recessive. In the same way the expectations based on pedigrees V, VII, VIII and IX, that the major defective women in them were homozygotes are likewise confirmed.

Pedigree XVII requires a special comment. In this family it was unfortunately impossible to test the first generation shown, since they were dead, but, in order to explain how the father (No. 2 in the second generation) can be a deviant deuteranope, while the mother (No. 3) is a green deviant and their daughter is green anomalous, while her brother (No. 4 in the second generation) is an ordinary deuteranope, we must assume that the parents of the first generation were as shown : the father green anomalous and the mother a hetero-zygote for ordinary deuteranopia. Thus the gene for green anomaly passed from grandfather to mother to daughter, and is dominant in the heterozygote gd', while the gene for ordinary deuteranopia passed from mother to son, segregating separately from the green anomalous gene in the same family. Any other theory would probably be more complex. The green anomalous condition would seem to be domin-ant to that of the deviant deuteranope again. Pedigree XVIIb shows that deviant deuteranopia breeds true to type.

A pedigree of special interest (XVIII) showed again the inde-pendent segregation of the green anomalous condition and deuteran-opia, and also (provided it was not a mutation) of the red anomalous

condition. Unfortunately the members of the first generation were dead, but it was believed that the man in this generation was normal, because he had been a railway employee (though not a driver). The second generation included two women who were green anomalous in typical form, and a man who was believed to be normal but could

(c) *Mother and Son.*

Pedigree XVIII.

♂ N? × ♀ ?

♂ N × ♀ g   ♂ N?   ♀ g × ♂ N?

♀ N (or H)   ♂ g   ♂ d   ♂ r   ♀ N × ♂ d   ♂ d?

♂ N?   ♂ N?
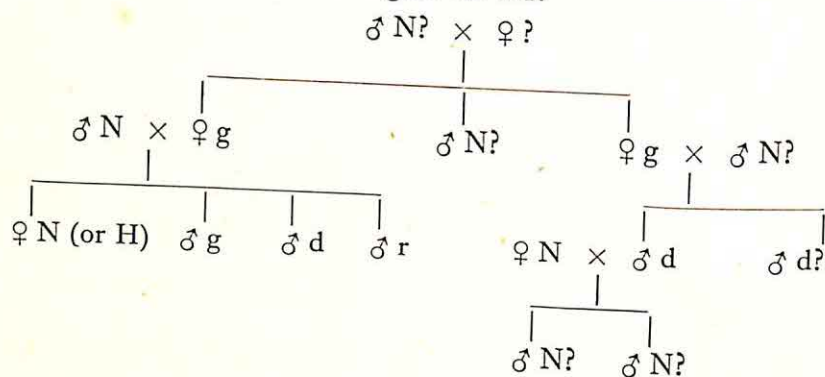
not be tested since he was dead. The two green anomalous women each married a man believed to be normal, the first because he had no difficulty with the Ishihara test, and the second because he was also a railway employee (though again not a driver). The first of these sisters had a daughter with perfectly normal colour vision, and three sons, one of whom was a deuteranope, one green and one red anomalous (red not darkened). The second sister had two sons, one a deuteranope exactly like his cousin, and the other believed to be a deuteranope because he was known to have confused red and green. The two boys in the fourth generation were believed to be normal but were too young to test.

In this pedigree it is clear again that the green anomalous condition must be dominant to deuteranopia in the two anomalous women, each of whom had a son who was a deuteranope, and who must have been heterozygotes for these two defects at least. It is interesting to see this demonstrated in the relationship of mother and son, as it was in the relationship of father and daughter previously. How it came about that one of the women in question had a red anomalous son remains a problem, but it is important that she also had a son who was green anomalous, thus showing the segregation of green anomaly and deuteranopia. It is surprising that the daughter (in the third generation) was perfectly normal, because it is almost certain

that she must have been a heterozygote, though of what kind it is not clear.

Pedigree XIX, again of mother and son, the writer was not able to verify in all respects, because the mother, who was said to be a protanope, was dead, and the other members of the family were not accessible, with the exception of the colour-blind man. Nevertheless he was a good informant and was fully aware of the details of his defect, describing his confusions of red with dark brown and black,

Pedigree XIX.

♀ p? × ♂ N?

♀ H? ♀ H? ♀ H? ♂ p × ♀ N?

♀ H? ♀ H?
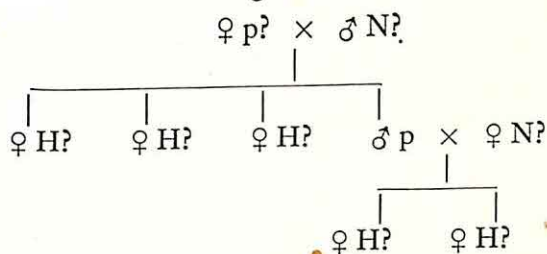
of certain yellows and greens, of pink with pale blue, and of blue, violet and purple, quite clearly. He was an extreme protanope. He described his mother's colour defects equally clearly, saying that it was necessary for somebody to choose coloured threads to match her sewing, and giving all the other details which left no doubt of her being a protanope. This pedigree is therefore worth including in the present book, although it does not add anything new to our information about the inheritance of colour blindness. If any of the daughters of the colour-blind woman had children, and if they could have been tested, it might have been possible to show whether she was a rare heterozygote, and thus to obtain information about the dominance order for protanopia and another defect, but it is quite likely that she was a homozygous protanope.

The frequent doubts about the distinct genetic status of the green and red anomalous conditions justify the presentation of Pedigree XX. A woman was a marked green deviant and was able to confirm that there were suspicions that her maternal grandfather had been colour blind. Three years later her brother came on other business, and the writer recognised his name, which was an unusual one, and immediately challenged him to undergo the colorimeter tests. He proved to be typically green anomalous. After this his other relatives were kind enough to present themselves, with the result shown in Pedigree XX. The other sister was normal, but the mother was a

green deviant and so was her sister, who also had three children. Of these one son was normal, the daughter was normal and the other son was typically green anomalous. Unfortunately the maternal grandfather was dead. In both branches of the family the fathers were normal. Here it is likely that the green anomalous condition was inherited from the maternal grandfather, and the corresponding heterozygous deviant condition appears in the mothers of the two green anomalous boys.

Pedigree XX

♂ g? × ♀ N?

♂ N × ♀ H   ♀ H × ♂ N

♀ H   ♀ N   ♂ g   ♀ N   ♂ N   ♂ g
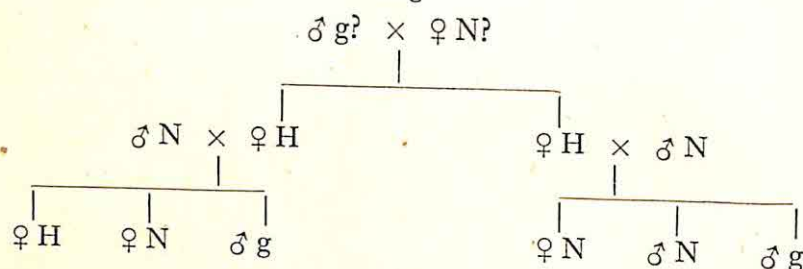
The precise magnitude of the major red-green defects is hereditary itself, because it is always the same in close relatives, except in those cases where father and son or father and daughter have different defects, which tend to prove rather than to refute the Mendelian principles. This precise inheritance of defects is most readily expressed in terms of multiple allelomorphs. The variability within each of these alleles will be due to the varying capacity of the genes to express their influence in the physiological environments provided by different stocks. Red-green blindness is decidedly variable, though the protanope, deuteranope and deviating deuteranope are clearly distinguishable, but all types of anomalous colour vision are relatively constant. The problems of the possible number of heterozygotes is very interesting. If it is true that there are six allelomorphs for human colour vision in its defective forms, then there must be many more than one kind of heterozygote among women, and if two loci on the X chromosome are assumed, as will be suggested below, then men must be capable of carrying two defective genes at a time. Most of the heterozygotes will, of course, be very rare, since about 86% of women are normal homozygotes and only a fraction of 0·5% are homozygous defectives. All the different heterozygous genotypes are included in the remainder, and the great majority of these will be normal heterozygotes. The number of double defectives among men must also be small. The fact that there are many heterozygous genotypes in women cannot account for all minor variations of colour

vision in their sex, because both sexes are equally variable when the heterozygous women are excluded. For the present it must not be assumed that all double-defective genotypes among men are major defective phenotypes.

Bell's data[31] collected from numerous sources are open, as she herself points out, to many possible criticisms, not the least of which may be the inadequacy of the tests used. All her cases correspond to expectations based on the theory of sex-linkage of Mendelian recessives. Even where the defect appears to pass from father to son, this theory is not necessarily contradicted, because the mother may have been a heterozygote.

The first case of special interest is pedigree 512 in Bell's list (Plate XXXVI). In this the father was a deuteranope and the mother was the sister of a deuteranope, but two sons were protanopes and two were normal. Neither of the mother's parents were tested, and it is not impossible that she herself was a heterozygote for protanopia derived from her father, while her brother was a deuteranope following their mother, who might have been a heterozygote for that condition. Pedigree 527 (Plate XXXVII) is also of exceptional interest. It shows two sons as protanopes, two as deuteranopes and one daughter as normal, from parents both said to have had normal colour vision. In such a case it is not improbable that the mother was a heterozygote for protanopia and deuteranopia together, and, since the father was normal, neither defect appeared in the daughter, who would have been a heterozygote for the one condition or the other. Another not dissimilar pedigree is 563 (Plate XXXVIII), in which one son was a protanope and one a deuteranope, while no information was given about the parents. Here again, the sons must follow the mother, and she may have been a heterozygote for protanopia and deuteranopia together, each son taking one defect. Pedigree 565 (Plate XXXVIII) shows father and daughter as deuteranopes, but there was no information of the condition in the mother's family. Whatever defect was latent in the mother, unless it was also deuteranopia, must have been recessive to that condition. None of these cases give any indication of a defective phenotype corresponding to the possible protanope-deuteranope heterozygous genotype. Indeed, if any conclusion about this phenotype could be drawn, however tentatively, it must be almost or completely normal.

Those cases shown in Plate XLI, which give evidence of the distinction between anomalous and red-green blind subjects, are exceptionally interesting. Pedigree 593 shows the separate segregation of the " protanomalous " condition and an undefined form

of red-green blindness. Separate segregation of deuteranopia and the " deuteranomalous " condition is shown by several pedigrees, while pedigrees 591, 595 and 597 show the inheritance of " deuteranomaly " and " protanomaly " as distinct allelomorphs to the normal condition. Pedigrees 594, 598, 600 and 601 all give strong evidence for the view that " deuteranomaly " is dominant to deuteranopia. In 594 the daughters follow the father who is " deuteranomalous ", while the son is a deuteranope, presumably following the heterozygous condition of the mother. In 598 the same state of affairs is highly probable, the great-grandmother being a heterozygote for deuteranopia, and two of her sons and four grandsons follow her (through a granddaughter who must have been a heterozygote for the same condition). On the other side of the family the daughter married a man who may have been " deuteranomalous " and they had a son who was a deuteranope, following his mother's genotype, and a " deuteranomalous " daughter, following her father's possible phenotype, while she had two sons, one " deuteranomalous " and the other a deuteranope. She must have been a heterozygote for these two conditions together, though in phenotype she was " deuteranomalous ", and each of her sons had one type of defect. In pedigree 600 we find a " deuteranomalous " woman (IV, 17, in the pedigree), descended from a " deuteranomalous " man and a woman herself possibly heterozygous for deuteranopia (but not from I, 2, who is the grandparent given in the pedigree). This " deuteranomalous " woman had two brothers who were deuteranopes (IV, 15 and 16). Again the defective woman is a heterozygote for deuteranopia and the " deuteranomalous " condition together, but the latter is dominant. Finally, in pedigree 601 the state of affairs is very closely similar, for the " deuteranomalous " woman (III, 8, in the pedigree) who had a " deuteranomalous " father and a mother who might have been a heterozygote for deuteranopia, was again a heterozygote for the two conditions together, so it seems, but " deuteranomaly " was the dominant.

In discussing these cases the terminology used by Bell (and many others) has been retained, but if we interpret " deuteranomaly " as green anomaly and " protanomaly " as red anomaly, it will be seen that the analysis lends strong support to the theory put forward in the present work, namely that the different genes for red-green major defects are multiple allelomorphs, and it provides no evidence which of necessity goes against that theory. In particular the analysis supports what was found in several cases discussed in this research, namely, that the green anomalous condition is dominant to deuteranopia.

THE TWO-LOCUS THEORY

Other work on this subject, reviewed by Gates,[16] strongly supports the multiple allelomorph hypothesis. There is evidence, from the data of Waaler[32] and others, that there may be two separate loci, one for " protanomaly " and protanopia, and the other for "deuteranomaly" and deuteranopia, and Franceschetti[34,35] extended the series by the assumption of separate genes for extreme " protanomaly " and extreme " deuteranomaly ". He has formulated the view that the two sets of multiple allelomorphs have dominance orders : N—PA—EPA—P; and N—DA—EDA—D (in which PA is used for " protanomaly " and so on for the other symbols). Subsequent investigations by Brunner and others tend to support this interpretation, though the dominance relationships do not always accord with those expected on Franceschetti's theory. It must be remembered that much of the previous work has been handicapped by limitations of the methods applied, and by lack of clear definition of anomalous colour vision as distinct from colour blindness. In the present research a serious attempt has been made to show which of the defective types may be regarded as discontinuous forms of variation and that they also segregate independently and are inherited true to type.[21] The application of the criteria put forward calls for a fresh study of the inheritance of colour-vision defects.

On the two-locus theory at least some of the combinations pg, pd, dr, gr (and presumably pd', d'r, d'r', dr' and gr', not hitherto recognised) should be normal, deviant or colour weak. This is actually claimed by advocates of the two-locus theory,[32] and is supported by Bell's pedigrees 527 and 563, and possibly by Pedigree XVIII in this book. As Gray has pointed out,[33] following Waaler,[32] a discrepancy of about o·2% in the observed frequencies of defective women, when 0·64% are expected on the single locus theory but only o·44% are found, might be explained in this way.

An interesting discussion of this problem has been published by de Vries,[19] and is based on the assumption that measurements of sensitivity with the flicker photometer enable us to draw conclusions directly about the proportions of " red " and " green " receptors in the eye. He assumed that " red blindness " is due to the loss of red cones, and " green blindness " to the loss of green cones, while red and green anomalous colour vision are due to the presence of " anomalous " cones. From this he is able to infer that the protanope-deuteranope heterozygote must be normal, and to make other inferences, namely that the dg, dp and dr combinations will also be

normal, without introducing the notion of dominance, but simply from a consideration of the numbers of different cones, which, according to his theory, must be present. It is, however, extremely difficult to base such a far-reaching speculation on a simple assumption of the Young-Helmholtz theory, and few even among its ardent supporters would admit direct estimates of the relative numbers of "red" and "green" cones from measurements of sensitivity. De Vries' conceptions also depend on a very generous idea of the variability of "normal" colour vision, and he assumes that it is evident that the protanope-deuteranope heterozygote must have normal colour vision simply because there would still be a 1 : 1 relationship in the numbers of "red" and "green" cones in her eyes. His assumption of "anomalous" cones also leads to increased difficulties, because it is not clear how red-green major defects can be explained in terms of losses of "red" and "green" cones, while anomalous colour vision would, if anything, be more easily explained by these losses. It is more likely that a special kind of defective cone would be required to account for red-green blindness than for anomalous colour vision.

The present investigation would suggest that the so-called "mutations" within the "P" and "D" series of alleles, which have been claimed by some writers,[16] might be produced artificially by the inadequacy of earlier methods of testing, for even the Ishihara Test, upon which many people rely, fails completely to distinguish between ordinary and deviant deuteranopes, between anomalous and colour blind, and in many cases between those with and without darkened red. The two-locus theory raises some interesting complications. Two of these complications are worth mentioning here : (1) That certain men might have two types of defective genes at the same time, in different loci of their X chromosomes, and that we know nothing definite about the effects of such combinations upon their colour vision; (2) That there would be two dominant genes for normal colour vision, one apparently producing its red and the other its green process in the phenotype.

Pedigree XVIII could be explained on the two-locus theory, because the woman who had a daughter of normal phenotype and three sons with different defects, and who was herself green anomalous, might have been a heterozygote for all three defects together. Since her sister was also green anomalous, and each had a son who was an ordinary deuteranope, it may be assumed that the two sisters were of genotype Nd/rg, and that the deuteranope sons were both Nd/—. The green anomalous son might be produced by crossing-over, and he would be of genotype Ng/—, while the red anomalous

son, also produced by crossing-over, might be rd/—. If we assumed that his genotype was produced without crossing-over, it would be rg/—, but red and green anomaly are opposite defects, and it is most readily assumed that a genotype in which they both occurred, such as rg/— in a man or rg/NN' in a woman, would be of normal phenotype, like the daughter in the same pedigree, who most probably had this genetic constitution. To the best of our knowledge d is lower in the scale of dominance in the one series of alleles than r in the other, and it is not unreasonable to suppose that r might have a stronger effect than d in the genotype rd/—, in which they are in different loci. There is another way of looking on this problem. The red anomalous phenotype may be viewed in this case as an expression of the only quality which the two genes r and d were able to produce in common. The most extreme red-green match possible for the particular deuteranopes in this pedigree was the only possible match for the red anomalous subject. Other red-green matches possible to these deuteranopes would also have been possible, some to normal, deviant or colour-weak subjects, others to less or more extreme deuteranopes, and their most extreme green matches to green anomalous subjects, but no others were shared with their red anomalous relative. Whether a similar principle might govern the effects produced by other combinations of genes in different loci is an open question.

If we wished to support a single locus theory it would probably be necessary to suppose that the red anomalous son was a mutant. The daughter of normal phenotype would then be one of the ordinary heterozygotes, Ng or Nd, who did not happen to show the characteristic slight defect. The pedigree is most likely to be regarded as favouring the two-locus theory.

It is worth pointing out that the combinations of genes to be expected in women, on the two-locus theory, are twenty in number for each of the two series taken separately, as shown in Table 123.* Since any of these pairs may occur together, however, the total number of possible combinations will be 10 × 10 = 100. For men the possible number of combinations of genes on this theory will be sixteen, and they are as follows:—N'N, N'p, N'r, N'r', dN, d'N, gN, pd, pd', pg, rd, rd', rg, r'd, r'd', r'g. The genes in each pair now, of course, are in different loci of the same chromosome.

The possibility of double-defective genotypes in men, some of which might be of normal phenotype, is supported by two cases discussed in previous chapters. One is represented in Pedigree VI.

* See footnote on p. 364.

Here a daughter who was a protanope had parents of normal pheno-
type. In the other case, shown in Pedigree VIa, apparently normal
parents had a red anomalous daughter. It has already been suggested
that the first result might arise from a combination such as that of
pd/— in the father with pN'/NN' in the mother. The protanope

TABLE 123*

POSSIBLE GENE COMBINATIONS FOR NORMAL AND DEFECTIVE COLOUR
VISION IN WOMEN ON THE TWO-LOCUS THEORY.

(The oblique lines separate genes which are located on
different chromosomes)

p/p				d/d			
r/p	r/r			g/d	g/g		
r'/p	r'/r	r'/r'		d'/d	d'/g	d'/d'	
N/p	N/r	N/r'	N/N	N'/d	N'/g	N'/d'	N'/N'

daughter would then have the genotype pd/pN'. The second result
might arise from the combination of rg/— in the father with
rN'/NN' in the mother, the red anomalous daughter having rg/rN'
as her genotype.

On the single-locus theory there would be the gene combinations
for women shown in Table 124, twenty-eight in number, while

TABLE 124

GENE COMBINATIONS FOR WOMEN ON THE SINGLE-LOCUS THEORY

NN						
Np	pp					
Nd	pd	dd				
Nd'	pd'	dd'	d'd'			
Ng	pg	dg	d'g	gg		
Nr	pr	dr	d'r	gr	rr	
Nr'	pr'	dr'	d'r'	gr'	rr'	r'r'

men would never have more than one gene out of the series at a time.
This theory would involve the possibility that certain combinations,
such as pd, as in Bell's pedigrees 527 and 563, and gd, in pedigree
XVIII of this work, are normal. In spite of this difficulty the single-
locus theory would be a more economical hypothesis if it could be
applied, but the evidence must be regarded as favouring the two-locus
theory.

* For the two-locus theory the symbol N' has been used to distinguish the normal
gene in the deuteranope series from the corresponding normal gene in the protanope
series, which is denoted by the symbol N.

FREQUENCIES OF WOMEN DEFECTIVES

Waaler[32] tested 9072 Norwegian girls, and found 0·441% of major defectives. He points out, as Gray has indicated,[33] that the difference between this percentage and the percentage expected on the single-locus theory, should correspond to the proportion of women of normal phenotype who on the two-locus theory carry genes from each of the two groups of defective alleles. The present writer and Mr. Robert Brown found 0.59% of defectives in 676 women and girls, a proportion which does not differ significantly from expectation on the single-locus theory. These statistics, however, are not based on a sample large enough to warrant a confident conclusion, especially as most workers have found fewer women defectives than would be expected on this theory.[16]

In his survey, Waaler found 40 major defective girls by chance, divided into the following classes : one deuteranope, three protano-malous and 36 deuteranomalous. He devotes an interesting section of his paper to the calculation of the expected frequencies of the different types of women defectives, according to the two-locus theory, on the basis of the frequencies observed among men. There is a good correspondence between these observed and expected frequencies.

In the present work an improved system of classification has been used, and a number of defective women were tested in addition to those who fell into the strictly random sample of women. The proportions of their various types were shown in Table 117, and it was pointed out that the random proportions of these types were distorted to some extent because a number of them were sisters. If those invited as sisters of defective women are excluded, and one protanope and one deviant deuteranope, who were reported to the writer on sound authority but not actually given the four-colour test, are added, their proportions may be compared with the corres-ponding frequencies of defective men, and this comparison is shown in Table 125. Here they have been grouped so that the expected frequency of women will not be less than five in any cell. The

TABLE 125

FREQUENCIES OF MEN AND WOMEN MAJOR RED-GREEN DEFECTIVES

	Protanopes and Red Anomalous	Deuteranopes	Green Anomalous	Totals
MEN	55	59	35	149
WOMEN	5	6	7	18

Chi-squared technique then shows that the proportions of men and women do not differ significantly, though the figures suggest more green anomalous women in proportion than men. This would be expected, because green anomaly is the dominant (apart from the normal condition) in the more frequent group of defective alleles. If the actual numbers of women were increased, but their proportions remained the same, the observed differences would tend to become statistically significant.

It is tempting to calculate the expected frequencies of women defectives, and, since this problem is certain to be raised again in later researches, a short paragraph may be devoted to it. On the single-locus theory the expected frequencies of women defectives would be represented by the expansion of the following expression, in which the letters represent the observed frequencies of the appropriate types of men :—

$$(N + g + r + d' + r' + d + p)^2$$

On the two-locus theory the calculation would involve :—

$$(N + r + r' + p)^2 \times (N' + g + d' + d)^2$$

In either calculation it would be necessary to group together the genotypes which were expected to correspond to each phenotype according to the dominance order, and to calculate the percentages appropriate to the observed frequencies of major defective men. There seem to be three difficulties in doing this. Firstly, although the dominance orders might be as indicated above, they are not known with certainty. Secondly, on the two-locus theory there are nine double-defective genotypes in men, of which the phenotypes are not known, though it might be assumed that at least some of them were normal. Thirdly, on this theory there are also double-defective genotypes in women, homozygous, such as pd/pd, and heterozygous, such as pd'/r'd', and some of these again might be of normal phenotype, but accurate knowledge on the matter is lacking. Although such calculations, especially that based on the two-locus theory, might be useful at a later stage in the research, in view of the small number of defective women available for comparison with the expected frequencies, and the difficulties mentioned, it seems best to leave the matter at this point.

CONCLUDING REMARKS

It is clear that the field for investigation of individual differences in colour vision is very large, and the writer hopes to organise a

survey of at least 10,000 men and boys and as many women and girls in the British Isles. These would be distributed in such a way as to enable comparisons to be made between different groups. Age, sex, occupation, geographical region, intelligence, art training, interests and personality differences would all be taken into account, and other points as well. The results would have considerable practical and theoretical value. The work should be extended to cover racial and other differences all over the world.

The problems of heredity of colour vision differences and defects are extremely interesting. With continuously distributed differences in the red-green and yellow-blue axes, for normal variations, and discontinuous variations depending on six defective allelomorphs which probably have two loci, for major red-green defects, the position is highly complex. It is most important to collect accurate and complete pedigrees for major defective women, and the writer hopes that any readers who think they can help will communicate with him.

The other main problem of this book, that of colour-vision theories, must be left to the judgment of the reader. Those who wish to limit themselves to three receptors for hue and none for brightness have many problems to solve, but it is important that they should try their best to succeed. The four-receptor theory, with a separate response-system for brightness, fits the facts with astonishing ease and adequacy, and requires no special pleading to support its claims.

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